Electricity Measurements

Chapter 15. Atmospheric Electricity

Abstract

Atmospheric electricity concerns the transport of charge in the atmosphere and the resulting effects. Its measurement requires knowledge of several different quantities, each of which spans a wide parameter space. Examples are the range of electric fields present between fair weather conditions and thunderstorms, and the range of charges between that of a single molecular cluster ion to that carried by a hailstone. Methods for measurements of atmospheric electric fields were amongst the first quantitative measurements in atmospheric science, beginning in the mid-eighteenth century. Modern techniques extend to remote detection of lightning from satellites, and local monitoring of lightning-induced electric field changes. The measurement of cluster ions is intimately linked to studies of cosmic rays and natural radioactivity, and provides a sensitive method of detecting hazardous radioactive releases. Atmospheric electricity measurements have utility for lightning detection, warning, and associated weather forecasting, and in investigating the electrical changes in air associated with aerosol and radioactive pollution. They also have applications to studying electrical effects in the lower atmosphere resulting from changes in the space weather environment.

Atmospheric electricity is sometimes interpreted as solely concerning the study of lightning, but is more inclusively defined as the study of all electrical phenomena in the atmosphere, regardless of meteorological circumstances. For most purposes, atmospheric electricity can be considered a study of the transport of charge in the stratosphere and troposphere under a range of meteorological conditions. Thunderstorms are in a sense the exception, as they occur in a restricted range of conditions and regions, in which large charges are separated in the presence of strong turbulent motions. Sufficiently large electric fields are generated to cause electrical breakdown as lightning and the release of acoustic energy as thunder.

15.1 Measurement principles and parameters

Measurements in atmospheric electricity extend across many different quantities, but can be usefully divided into those made for disturbed weather (i.e. thunderstorm) and fair weather conditions. For disturbed weather purposes, a variety of measurement systems have been developed for detection of the lightning discharge itself, optically, electrostatically or through use of radio frequency emission. In contrast, for fair weather, when no appreciable charge separation is occurring, the vertical electric field and the associated vertical current density are the principal quantities of interest. Fair weather atmospheric electricity has also traditionally included the conduction properties of air, such as the generation, concentration and properties of the cluster ions it contains. The typical parameters considered are listed in Table 15.1.

Table 15.1 Measured parameters in atmospheric electricity

Parameter	Description	Unit	Symbol
Vertical electric field	vertical electric force acting per unit charge	V m^{-1}	E_z
Potential Gradient	conventional description of vertical electric field	V m^{-1}	F (or PG)
conduction current density	vertical current flowing per unit area due to conduction	pA m^{-2}	J_c
air conductivity	conductivity of air due to both negative and positive ions	fS m^{-1}	σ
mean ion mobility	drift speed of a cluster ion per unit electric field	m^2 V^{-1} s^{-1}	μ
mean ion number concentration	number of ions per unit volume	m^{-3}	n
ion production rate	rate of generation of bipolar ions per unit volume	m^{-3} s^{-1}	q
charge density	net concentration of charge per unit volume	C m^{-3}	ρ
elementary charge	modulus of the charge carried by an electron	C	e

15.2 History

Atmospheric electricity is amongst the oldest experimental topics in meteorology, with the globally iconic work of *Benjamin Franklin* (1706-1790) providing a useful date, 1752, with which to define the beginning of the modern era of work. Franklin's international reputation ensured his suggestions for experimental investigations were widely noticed [15.1].

Soon after Franklin's work became known, experimenters found that electrification remained present away from the immediate location of thunderstorms. The astronomer *Pierre Charles Le Monnier* (1717-1799) detected electrification in clear air in 1752 [15.2], and in June 1753, *Guillaume Mazeas* showed that a silk-insulated 100 m horizontal wire suspended 10 m above the surface would nevertheless acquire charge in dry, non-thunderstorm conditions [15.3]. Later that year, electric charges in a cloudless atmosphere were detected by *John Canton* (1718-1772) [15.4]. Canton developed further apparatus to investigate charges associated with hail, snow and rain. Remarkable studies were made with the early instrumentation, such as a series of continuous observations made by *Giambatista Beccaria* (1716-1781) in Piedmont, north-west Italy [15.5], and two years of daily observations made by *John Read* (1726–1814), using a vertical rod mounted above his house in Knightsbridge, London [15.6, 15.7].

Early measurement instruments often used a flame as a method to acquire the local potential of the air, connected to a mechanical electrometer. The need for a method of continuous measurement of the vertical atmospheric electric field was recognised by *Lord Kelvin* (born *William Thomson*, 1824-

1907), who developed a continuous recording system based on a "water-dropper" sensor for the atmospheric potential with a photographically registering electrometer. The spray of drops generated by the water-dropper exchanged charge with its surroundings, ultimately equalising the potential of the isolated pipe supplying the water spray, which was measured [15.8]. This continuous operation represented a significant advance over the flame probes. The Kelvin water dropper potential equaliser was widely adopted internationally, including at the top of the Eiffel Tower [15.9], and for use on manned balloons [15.[10]]. Remarkably, an operating Kelvin water dropper survives and is still in routine service at Kakioka Observatory in Japan (fig 15.1). Note that the magnitude of the vertical component of the atmospheric electric field E_z is commonly referred to as the *Potential Gradient* (PG), which is, by convention, regarded as positive in fair weather.

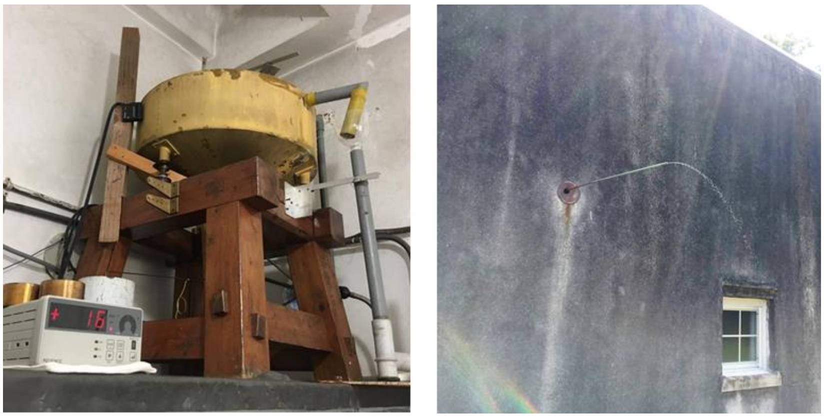

Fig 15.1. Potential Gradient measurements made using the Kelvin water dropper potential equaliser, at Kakioka Observatory, Japan. (Left) Isolated water dropper header tank, with electrometer measuring tank potential. (Right) Water dropper spray, generator from an isolated tube emerging from the observatory wall. (Photo: R.G. Harrison)

The widespread need for fair weather measurements at many international observatories led to more commonality in the technology used. Kelvin water droppers were used at some sites for PG, but they were superseded by radioactive probes (e.g. at Porto and Lerwick), which permitted continuous measurements without the need for a water supply and associated frost protection. In the second half of the twentieth century "field mill" instruments became increasingly commonly used for PG measurements. These avoid the regulatory issues arising from the use of ionising radiation on radioactive probe sensors. Many commercial field mills exist and are now in use, and some have proved very durable in hostile atmospheric conditions.

Of particular importance for atmospheric electricity measurements was the lead given by the Carnegie Institution which developed techniques for use on survey ships, and in particular, the *Carnegie*, an oceanographic and geomagnetic survey ship. The Carnegie's cruises between 1909 and 1928, when the ship was destroyed by fire, included routine measurements of air ion concentration, air ion mobility and PG. The common diurnal variation in PG found across the planet in fair weather conditions is still known as the *Carnegie curve* [15.11].

15.2.1 Early measurement technologies

Electrometers are devices designed to measure small amounts of charge. The earliest electrometers were a pair of pith balls, attached to each other by a thread hung centrally on a hook. When the balls became charged, they repelled by an electrostatic force, with a separation distance which is non-linearly proportional to the charge carried. Absolute calibration is possible if the arrangement is described in detail, for example to allow retrieval of the potential from historical measurements [15.12]. Later designs of mechanical electrometers used gold leaf or straw as the sensing elements, again with the mechanical deflection under an electric force measured to obtain the charge. Using delicate bearings and sensitive torsion measurement, precise measurements of small charges could be made e.g. in a device made by Kelvin, [15.8]. Attaching a mirror to reflect and move a light beam provided a method of amplification and recording for the small changes detected. This approach was used by the recording part of the Kelvin water dropper system, and for the PG measurements on the final cruise of the *Carnegie*.

During the early twentieth century new technologies were developed and many geophysical observatories internationally adopted methods for atmospheric electricity measurements. The Nobel Laureate *Charles* ("*C.T.R.") Wilson* devised a method to obtain regular measurement of the vertical current density current and PG using a horizontal plate system, which was deployed at Kew Observatory from 1909, continuing in regular use for almost 70 years [15.13]. There has also been considerable longevity for the operating principles of a portable ("Gerdien") device designed for air conductivity measurement [15.14], using an aspirated cylindrical capacitor instrument to determine the air conductivity by rate of decay of charge on an electrode exposed to air.

Some of the first sensors for lightning detection used the response of a capillary electrometer to <20 Hz changes in atmospheric field, recorded on a photographic plate [15.16]. Wilson's investigations focussed on determination of lightning charge moment, with the signal authenticity and range determined from acoustic methods, limiting the maximum range to less than 30 km. Similar techniques were used to investigate characteristics of the lightning electrostatic field change such as polarity and shape [15.17]. The arrival of early radio frequency (RF) lightning detection methods in the mid-twentieth century, combined with an extended human weather observation network, were used to investigate lightning signals beyond audible range [15.18]. As instrumentation and techniques developed during the late twentieth century, the electrostatic field change associated with lightning could be used to estimate the location of charges neutralised by lightning in three dimensions [15.19]. Increased sensitivity of electronics and digital filtering enabled the electrostatic field change (below 50 Hz) associated with lightning to be used by commercial instrumentation to estimate thunderstorm range 100 km from the sensor [15.20].

15.2.2 Developments in measurement technologies

Developments in electronics provided alternatives to mechanical electrometers. Between about 1920 and 1960, thermionic valves provided the basis for measuring small charges or from voltage sources which were unable to supply current (i.e. high impedance voltage sources). The thermionic valve operated by deflecting a current from a heated electrode operating at low pressure, through the action of an electric field. By careful construction, the leakage current of the enclosing glass envelope was small, and the voltage to be measured caused deflection of the current with negligible current drawn. This leakage was further reduced by the use of coatings on the electrodes. Valve electrometers were durable electrically, although physically fragile, and well suited to fair weather measurements [15.22].

Transistors replaced thermionic valves in the second half of the twentieth century, with the properties of the semiconductor junction defining the usefulness of a device for measurements. In many ways the field effect transistor closely replicates the operation of a thermionic valve, but its departure from ideal behaviour, from, for example, the effect of leakage currents, restricts its use in electrometry. A major limitation is that the most sensitive semiconductor devices tend to be highly restricted in dynamic range, which can render them badly damaged by overload conditions. For use in atmospheric electricity, when transient conditions can occur unexpectedly, this can be a severe disadvantage. The overall complexity of a semiconductor measurement circuit may therefore be dictated by additional protection devices which must be included for reliability.

Semiconductor electrometers can be used for measurement of charge, current and voltage. They typically use a standard integrated circuit element - the operational amplifier - which has been optimised to minimise the sensing current drawn, typically in the range of 1 to 10 fA. Operational amplifiers use feedback to provide close to ideal performance, and the feedback element is chosen for the quantity to be measured. If a capacitor is the feedback element, the device can typically measure charge, and if there is a feedback resistor, current can be monitored [15.23]. Voltage measurements and amplification can also be achieved [15.24], which can be extended over a wide range with additional circuitry [15.25,15.26]. One important consideration in electrometry is the size of the feedback resistor required. To provide an output voltage of 1 mV from a 1 pA current, a 1 GΩ resistor is required. Generally, stable resistors in the range from 1 GΩ to 1 TΩ can be difficult to obtain. It is possible to synthesise these large resistor values using more standard components, but other disadvantages arise depending on the circuit configuration.

15.3 Theory

The description of quantities in atmospheric electricity requires consideration of the fair weather parameters and disturbed weather parameters separately. In the fair weather case, the quantities of electric field, conduction current density and air conductivity can usually be related by Ohms Law, in the absence of turbulence. In the disturbed weather case, the lightning source position and the flash rate are the primary quantities to be determined for operational meteorology, but the lightning currents and surface electric field changes are important for research.

15.3.1 Fair Weather Fundamentals

In this section the fundamental measured parameters of fair weather atmospheric electricity are presented.

The *Potential Gradient* (PG) is essentially the primary quantity considered in fair weather atmospheric electricity. It is a determination of the vertical component of the atmospheric electric field. In fair weather conditions, the electric potential increases positively with height. If the potential is considered to be zero at the surface, the potential in fair weather at one metre above the surface is of order 100 V. The PG near the surface is conventionally considered to be the difference in potential between a point at 1 m and the surface, i.e.

$$F = \frac{\Delta V}{\Delta z} \qquad (15.1)$$

for F the potential gradient, Δz the difference in height, and ΔV the associated change in potential. A consequence of this convention is that the vertical electric field E_z differs from the PG by a minus sign, i.e.

$$F = -E_z \quad . \qquad (15.2)$$

In fair weather, the PG is therefore positive, and the electric field negative. During disturbed weather, the PG can become large and variable, in magnitude and sign. In these cases the PG is responding to local charge separation and induced effects, whereas, in fair weather, it arises mostly from the conduction current passing through the finite conductivity of atmospheric air.

Atmospheric air has a finite electrical *conductivity* because of the presence of molecular cluster ions, formed by the combined effects of terrestrial radioactivity and cosmic ray ionisation. Near the surface over the continents, cluster ions are generated by the ionisation of air molecules from high energy interactions, either from gamma emitting sources in the soil or alpha emitting isotopes of radon released through porous surface materials. There is also a small contribution from cosmic ray ionisation, which increases with increasing height. Over the oceans, the principal source of atmospheric ionisation is from cosmic rays. The typical surface ionisation rate, found by an ionisation chamber (a fixed volume device in which the rate of charge generation is measured), q is 10 ion pairs $cm^{-3}s^{-1}$, about 20% of which is due to cosmic ray ionisation. Cluster ions have traditionally been categorised by their electrical mobility, which is their drift speed in a unit electric field. This has led, historically, to the distinction between small (or fast) ions and large (or slow) ions, and further categories have also been proposed. Small ions have a mobility of about 1 cm^{-2} V^{-1} s^{-1}, and they provide the greatest contribution to the electrical conductivity of air of atmospheric charged particles. Large ions would now be considered to be aerosol particles which have become charged, for example after a collision with a small ion.

The number concentration of small ions in atmospheric air determines the conductivity of air. If there are *n* ions per unit volume of mean mobility μ, the total conductivity σ is given by $\sigma = 2n\mu e$ where *e* is the elementary charge. The factor of 2 accounts for the contribution of the positive and negative ions, which are assumed to have similar concentrations and values of mobility. If there is appreciable asymmetry in the ion properties, the individual contributions of the bipolar ions can be considered separately.

Air conductivity can also be considered in terms of an Ohm's Law relationship for conduction, considering the vertical electric field E_z and vertical current density J_z, as

$$J_z \quad = \sigma E_z \quad . \qquad (15.3)$$

This only applies if Ohmic conduction occurs, and will not be valid in other circumstances, for example if there is a turbulent component contributing to the charge transport. Note that, in this equation, the electric field convention is used: the conduction current density is found to be directed downwards in fair weather.

The air-Earth *current density J* describes the total vertical electric current flowing between the atmosphere and Earth's surface. This current is measured directly using an electrode - often an isolated flat horizontal plate - exposed to the atmosphere. A sensitive and high impedance ammeter attached between the electrode and ground records the current.

In general, this current has four contributing components [15.2]. Firstly, there is the conduction current [15.27] [15.28]. This is the near-vertical current which flows between the lower ionosphere and Earth's surface due to the action the global electric circuit [15.29]. The conduction current component can be found indirectly by measuring the air conductivity and electric field, with current inferred using Ohm's Law [15.30] [15.31]. Turbulent motion of space charge within the atmosphere, charged regions in overhead cloud and lightning transients combine to induce the second prominent component of the Air-Earth current, called the displacement current. Whilst this component is induced on the sensing electrode rather than a flow of charge from the atmosphere, the continuous and broad spectra of variability of the atmospheric electric field means this current must be carefully considered in direct current measurements. The third component is that produced by turbulence, whereby ions and charged particles are transported by the movement of air. During disturbed weather, charged droplets, particles or pellets falling on the electrode will produce the fourth component, referred to as the precipitation current. If the collecting electrode has sharp edges, an additional disturbed weather component may also be produced under a strong electric field, where point discharge (corona) is initiated. Point discharge can produce currents several orders of magnitude greater than the conduction current [15.19], so electrodes need to be smooth to avoid such contamination from additional current sources.

Of all these components, it is the conduction current (or rather the conduction current density) which is of most significance to investigation of the global electric circuit, due to its origin from the potential difference between the ionosphere and surface. The small magnitude (~ 1×10^{-12} Am^{-2}) of the currents brings with it a requirement for maintenance of extremely good electrical insulation between the electrode and ground under all weather conditions; the need to eliminate other unwanted current components makes the conduction current density a challenging parameter to measure.

15.3.2 Disturbed Weather Lightning Detection

In contrast with the fair weather current, the current flowing as a result of a lightning discharge is very many orders of magnitude greater. Methods of remote detection of lightning are discussed here, using radio frequency, optical and electrostatic techniques, as well as the acoustic energy generated.

The complete process of charge transfer during a single lightning discharge is called a *flash*. A flash neutralises a portion of charge within a thunderstorm, which can be readily identified by a sharp change in the cloud's electrostatic field over a typical period of 0.2 s, followed by a much slower recovery of order 100 s, as electrification mechanisms within the cloud replace the neutralised charge. The complete discharge process during a flash does not produce a smooth current flow, but is instead composed of several discrete surges of current lasting a few tens of milliseconds, referred to as strokes. After initial electrical breakdown of the air, a lightning channel is formed by a trail of electrons, called a leader. These leaders are only weakly luminous and will split and change direction after several metres in steps. These steps in channel propagation give rise to the name of the first stage in a lightning flash - the stepped leader. Once the lightning channel has been formed by the leader, current surges along it in discrete pulses, or *strokes*. When the lightning channel is from the cloud to ground (CG), the initial stepped leader creates a pathway for the return stroke. This stroke is often very powerful, generating a typical peak current of order 10,000 A and occasionally exceeding 200,000 A. Currents of this magnitude produce a bright channel and quickly heat the air, producing the shockwave recognisable as thunder. More commonly, a lightning channel remains within the cloud and the resulting strokes are termed intracloud (IC) or cloud-to-cloud (CC). Charge transfer between the cloud and nearby cloud-free air also occurs, as well as leaders which originate from the ground, transferring charge to the cloud overhead and are consequently termed “upward” or ground-to-cloud lightning. Lightning strokes can be of either positive or negative polarity. The polarity of a cloud-to-ground stroke is determined by the charge it lowers from the cloud to the ground. Since the base of a thundercloud is normally negatively charged, most CG strokes are of negative polarity (-CG). CG strokes with positive polarity tend to originate near the top of the cloud where a large reservoir of positive charge is often found. A positive cloud to ground stroke (+CG) is on average the most powerful type of lightning stroke on Earth, responsible for significant damage and emission of radio signals that can be detected thousands of kilometres away. For radio detection of lightning, it is the stroke which is the fundamental property detected so the location and count rate of radio-based detection systems will by default relate to strokes, not flashes. Since a single flash is typically composed of 2 to 5 (and occasionally more than 20) strokes, it is important to consider that other detection systems such as human observation or electrostatic techniques will consider lightning discharges in terms of complete flashes. This can, and often does, lead to confusion when comparing the output of different types of lightning detection techniques.

Radio frequency (ULF to VHF)

Lightning emits a broad spectrum of electromagnetic radiation, which can be used for location and remote determination of the discharge properties [15.32]. Since different components of a lightning flash emit radiation with different effectiveness at different frequencies, researchers can optimise their radio receivers to have greatest sensitivity to bands within the spectrum according to their area of interest [15.33] [15.34] [15.32]. For example, the initial ground-seeking leader stroke (stepped leader) and short, in-cloud leaders tend to emit most effectively in the very high frequency (VHF) band, whereas the subsequent visible, high current surge along the leader’s channel associated with the powerful return stroke emits strongest in the very low frequency (VLF) band [15.35]. Such differences are important factors in determining the maximum range and detection efficiency of radio-based lightning location instrumentation [15.33].

Whenever electrons are accelerated, electromagnetic radiation is produced. The greater the acceleration and number of electrons involved, the greater the radiated energy. The rapid acceleration of numerous electrons in a lightning channel at the start of a return stroke will therefore be expected to generate a signal of high power, albeit for a duration of only a few milliseconds [15.32]. The ionised lightning channel can be considered as an antenna, the length of which influences what frequency will be most effectively radiated. The ~ 10 to 100m steps in a channel of the downward-propagating stepped leader prior to a cloud-to-ground return stroke act as a set of similarly-sized antennas. Such antennas radiate energy most effectively at wavelengths twice their length, equating to typical peak emissions of order 10 MHz in the HF band. Steps energised by weak intracloud strokes can be even smaller, with length-scales under 10m and emitting strongest in the VHF band [15.36]. Once a return stroke is initiated by contact with an upward streamer near the ground, a surge of electrons propagate back up the ionised channel of the stepped leader. This channel can be several kilometres long, so will radiate most effectively at much lower frequencies than the stepped leader or intracloud stroke. These near-vertical, long channels act as monopole antennas above the conductive ground, emitting most effectively for wavelengths four times their length, typically around 10 kHz, in the VLF part of the radio spectrum [15.37] [15.34].

The ionosphere is an electrically conductive layer of the atmosphere beginning at an altitude between 60-90 km, depending on properties such as solar intensity. The ionosphere acts as an effective reflector of very low frequency radio signals such as those from lightning return strokes. Powerful VLF signals can propagate over thousands of kilometres through the atmosphere since they are reflected between the ionosphere and surface instead of being strongly absorbed or lost to space (see fig 15.2) [15.35][15.38]. Such propagation properties and powerful emissions from return strokes are exploited by long-range lightning location networks, where VLF receivers are deployed across a large region and capable of locating lightning over continent-scale regions, or more [15.39] [15.40] [15.41]. Lightning is located by comparing the arrival time differences of the same signal received at multiple receivers, sometimes in combination with triangulation using magnetic direction finding (fig 15.2). The location accuracy of such long-range VLF arrival time difference (ATD) networks depend on the validity of their signal propagation model, receiver baseline (spatial density of receivers) and how accurate they can time the arrival of the same lightning signal arriving at the receivers (e.g. [15.39]). In reality, median location accuracies of 1-20 km are typical of this long-range location method, although higher density continental-scale networks with higher frequency upper limits (LF/VLF) can achieve median location accuracies of order 100m. The necessity to use VLF for long-range lightning location means that such networks are normally strongly biased to CG lightning stroke detection, although most are also capable of locating strong intra-cloud activity as well. Shorter baseline, higher density networks incorporating the LF band have been demonstrated to detect, and discriminate between, both CG and IC/CC lightning strokes with peak currents as low as a few hundred amps.

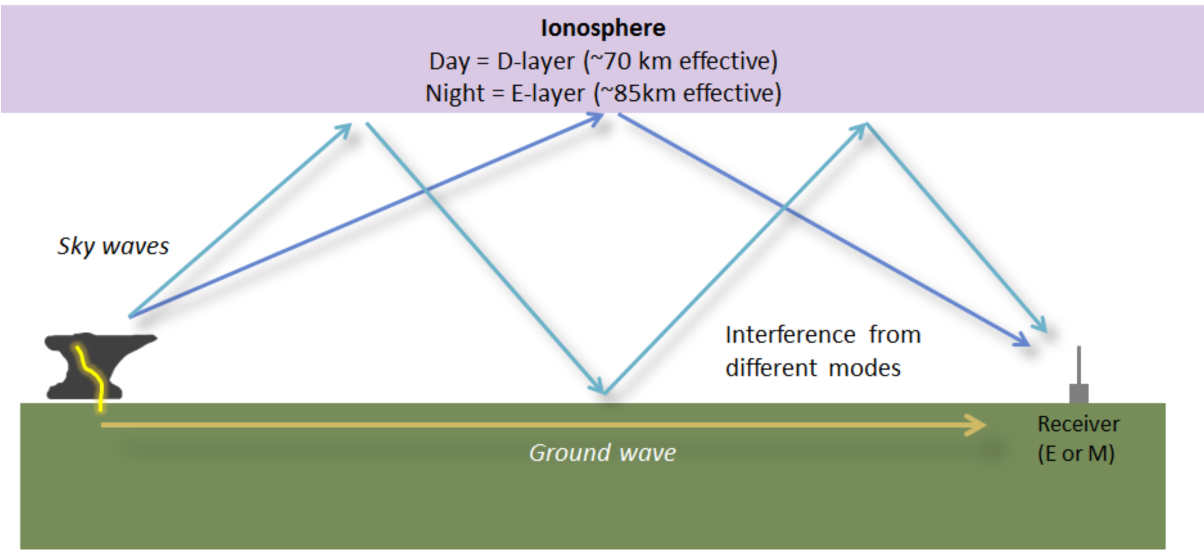

Fig 15.2. Reflection of VLF waves by the ionosphere

In addition to accurate lightning location using VLF/LF networks, it is possible to detect the shape of individual lightning channels in three dimensions using a short-baseline (of order 10 km) network of VHF interferometers [15.36]. Such networks are tuned to the weaker components of the lighting discharge process and cannot exploit ionospheric reflection, so their range is little more than line of sight, at approximately 200 km. The VHF network technique does however allow exceptional detection efficiency and location accuracy (of order 10m) over the relatively small area covered, making it popular with lightning research groups. In addition to scientific research, VHF interferometry is also used on some regional-scale lightning location networks for the purpose of total lightning (CG, IC and CC) detection, especially when detection of weak IC strokes or initiation height is important. The short baselines required normally limit this technology to coverage of smaller countries or regions compared to the more continental-scale VLF/LF networks, although some near-global network providers incorporate VHF receivers if they have the capability of deploying a suitably dense network of receivers over a wide geographical area. VHF signals from lightning can propagate through the ionosphere, where they can also be detected by space-based lightning detection instrumentation for scientific research.

The proximity and direction of lightning strokes using a single radio receiver is possible and can be a useful indicator of local thunderstorm activity. The range of such instrumentation is normally limited to a few hundred kilometres and location accuracy is generally poor compared to using a network due to the assumptions required on lightning signal characteristics and propagation. False alarms can arise due to nearby anthropogenic sources of radio transients (e.g. [15.38]), and can be removed by requiring corroboration from multiple receivers in a network. The presence of ferrous material and conductive paths where currents can be induced at a site can generate systematic and angular-dependent errors in lightning direction estimation from single-site receivers of up to 30°, unless these errors are determined and accounted for by prior comparison with an independent method of lightning location. Range is normally estimated by comparing the amplitude of one or more radio frequency bands, although large uncertainties exceeding 10 km can result from the natural variability of lightning radio emission characteristics.

Given there are typically 2000 active thunderstorms on Earth at any time, the global atmosphere is subject to near-continuous excitation by lightning. Larger lightning strokes radiating strongly below VLF frequencies act to excite the waveguide between the surface and ionosphere, causing it to resonate. The fundamental frequency of this resonance is 7.8 Hz in the extremely low frequency (ELF) band, with six harmonics below 50 Hz [15.42] [15.43]. These near-continuous peaks are called *Schumann Resonances* and since they are a global signal they can be measured from any location on Earth [15.44]. Their small amplitude can limit detection to sites with low background electrical noise, where the diurnal cycle of the resonance amplitude can be used to infer general characteristics of global lightning activity such as diurnal and seasonal variability. Both electric and magnetic field components of Schumann Resonances have been used for lightning, ionospheric and radio propagation research (e.g. [15.38]).

Electrostatic

Neutralisation of charge during a lightning flash occurs over a time period of approximately 0.2s, producing a step-change in the electrostatic field of a thunderstorm ([15.17] [15.18]). This step is gradually removed as the cloud is re-energised, producing a recovery curve lasting for more than a minute. Due to the image effect of the conductive surface below, the change in charge can be represented as a vertical dipole, of length twice the height of the neutralised charge region above the ground [15.16]. The total charge neutralised by a lightning flash can therefore be given in terms of charge moment when using quasi-electrostatic measurements. Whilst the change in electric field measured at the surface can exceed 100 kV m^{-1} in the first second after a flash within a few kilometres, this dipole field quickly attenuates with distance, with magnitude proportional to the inverse cube of distance from the dipole. As a consequence, electrostatic lightning detection is usually limited to a range of less than 100 km before any signal is lost to background noise. Such a distance is however sufficient for warning of local thunderstorm activity around a site, with automatic electrostatic lightning detection and ranging instrumentation available commercially [15.45]. Every lightning flash will produce a step change of thunderstorm electric field so this method of lightning detection from a single sensor is capable of detecting all forms of lightning activity (CG, IC, CC) within a few tens of kilometres from the storm with very high detection efficiency. Providing that the electrostatic field is sampled at a rate of at least 10 Hz (ideally 100 Hz) it is possible to estimate the distance to the lightning flash using the maximum electric field change and an assumption of the charge moment. Note that such sampling frequencies limit time resolution of the lightning discharge to the flash, not stroke, level. Higher sampling rates risk contamination from the electromagnetic component of the emission and lower sampling rates risk under-sampling of the signal, causing the true magnitude of electric field change immediately following the flash to be underestimated.

Whilst using a fixed value for lightning strength to estimate the distance to a flash based on signal amplitude would produce unacceptably large errors for a radio-receiver, such an assumption is more acceptable when using electrostatic detection. This is due to the inverse-cubed reduction of signal strength with distance for the electrostatic dipole field, which acts to limit the effect of natural variability in lightning charge moment on range uncertainty compared to radio peak amplitude, which reduces by a lower inverse power of distance (between 1 and 2 depending on propagation characteristics). For example, it is possible to estimate the distance of a 20 km flash with a typical uncertainty of 5 km using the electrostatic field change alone. Flash direction cannot be readily determined from magnitude of the electrostatic signals alone.

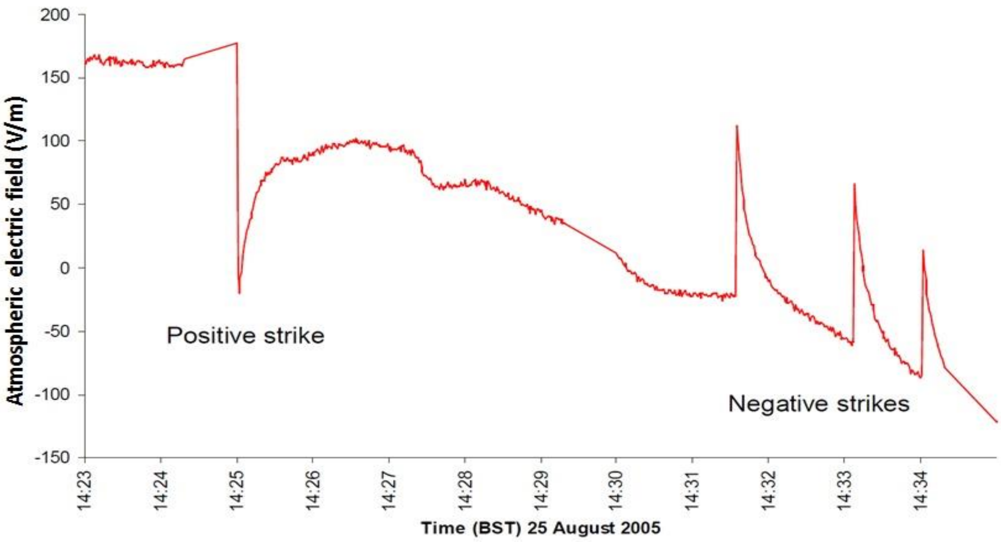

Fig 15.3 Electrostatic field changes associated with lightning flashes approximately 10 km away, recorded by a JCI 131 field mill. (From [15.46]).

Optical

In addition to qualitative lightning detection by human observation, optical sensors can be used to monitor lightning activity from the surface, atmosphere or space [15.47]. Selecting a wavelength of strong emission by lightning compared to sunlight allows optical observation of lightning even during the daytime. The wavelength of choice is at 777.4 nm. This corresponds to the optical emission of oxygen, excited in the plasma of the lightning channel. Optical detection is not generally used in isolation for automated ground-based thunderstorm warning systems, but is instead used as an independent confirmation of nearby lightning for single site detectors where electric or radio noise can trigger false alarms. Obscuration of the optical signal by nearby objects and cloud limit the effectiveness of ground-based optical detection for distant lightning. An important use of optical lightning detection is on satellites, where the ability of an optical signal to pass through to space largely unaffected by the upper atmosphere is of benefit compared to lower frequency radio signals. Continuous optical lightning detection from polar-orbiting satellites has been available since the mid-1990s, with this proven technology being deployed on geostationary platforms as part of combined atmospheric monitoring missions from the late 2010s. The brightness of the 777.4 nm emission within thunderclouds can be mapped with high resolution cameras on board geostationary satellites to estimate lightning location in real-time over continent-scale regions at a spatial resolution of 5 km for low latitudes, although closer to 30 km at high latitudes due to the less favourable viewing angle. An advantage of space-based optical detection of lightning is the ability to observe weak intracloud flashes near the top of the cloud, which can sometimes be a precursor for more intense lightning activity. However, the optical signal from strokes nearer the cloud base can be strongly attenuated be the cloud above, leading to the possibility of reduced detection efficiency of such events, especially during bright sunshine.

Acoustic

The explosive heating of air adjacent to the hot plasma within a lightning channel produces the shockwave familiar as the sound of thunder. The longest archive of thunderstorm activity extending over two centuries is provided by “Thunder Days” records, where the occurrence of thunder heard by a human observer was recorded by a weather service or a weather diarist. Thunder can only be heard within approximately 20 km of the lightning flash if the site is quiet and the observer is outside, with a maximum range of more like 10 km for indoor environments. Thunder Day records are therefore of variable quality depending on the observer’s ability to perceive the thunder, but are nonetheless a valuable addition to long term climatological records, especially prior to the commencement of automated lightning location networks in many developed countries during the 1980s. A particular feature, despite their simplicity, is that the detection sensitivity is constant providing stable records for climatology, whereas lightning networks are generally regularly upgraded.

Lightning range can be estimated to within a few hundred metres by manually recording the time difference between the visible flash of lightning and subsequent arrival of thunder, using the speed of sound in air for the environmental conditions, for example 343 ms^{-1} at 20°C. This range includes the height of the source too, so high altitude intracloud flashes may be difficult to hear at ground level despite them occurring overhead. Sound propagation effects due to temperature gradients and echoes will introduce uncertainty in range estimation. Due to the short range and difficulty in automatically discriminating between thunder and other sources of similar noise mean that this technique is not used for automatic lightning detection and ranging.

15.3.3 Precipitation electricity

Convective precipitation is capable of producing strong and rapidly varying electric fields at the surface, due to charge carried to ground on precipitation. Although the total charge transferred between the cloud and ground my precipitation is small relative to other mechanisms such as lightning and point (corona) discharge [15.48], it is considered as a possible mechanism for the triggering of lightning [15.49].

Raindrop charging

The first continuous measurements of the electrical charge on rain were conducted over 100 years ago by Simpson [15.50] in Shimla, northern India, during the monsoon seasons of 1907-8. Simpson's apparatus consisted of an electrically insulated rainwater collector connected to a recording electrometer, which registered the charge accumulated on the collector every two minutes. This was converted to a charge per cubic centimetre of rainfall by measuring the collected rainwater volume using a tipping bucket rain gauge. Simpson reported that 71% of the rainfall associated with monsoon showers and thunderstorms was positively charged, at typically 300pC per cubic centimetre of water, generating a typical current density to Earth of order 1nA per square metre. These values are in accordance with more recent observations [15.51]. He also noted that although the heaviest rainfall during the storm was positively charged, there was no clear relationship between charge magnitude and rainfall intensity. The reason for this charge was considered by Simpson to be the result of droplet break-up in strong updrafts, with the falling raindrop retaining a positive charge and the liberated negative ions or smaller droplets travelling upwards in the updraft.

Simpson's explanation for the origin of charged rainfall was contested by C.T.R Wilson, who instead proposed that the predominant positive charge on convective rainfall resulted from the selective capture of positive ions by the raindrops as they neared the ground [15.52]. According to Wilson, the negatively charged base of Cumulonimbus clouds attracted an upward flow of positive ions. The raindrops falling below this cloud base were polarised by the negative charge above them, resulting in a negative charge on their lowest surface. The positive ions were attracted to the negatively charged drop's underside, causing the drop to acquire an overall positive charge by the time it reached the ground. The charged rainfall measured at ground level was therefore considered by Wilson to be the result of the charge distribution within the cloud, rather than the cause, as previously assumed. Nonetheless, Simpson explained his later finding of positively charged regions near thunderstorm cloud bases as being the result of raindrop break-up in strong updrafts [15.53]. The long-standing discussion between Wilson and Simpson on precipitation and thunderstorm charge structure presents one method for summarising the development of the subject [15.54].

Wilson's proposed ion capture mechanism for raindrop charging was recognised by Simpson when he discovered that the charge on rainfall at the surface often mirrored that of the electric field, which in turn related to the charge near the cloud base [15.55]. This "mirror image effect" was thought to be due to the rain drops charging by scavenging of ions liberated from the surface as a result of point (corona) discharge during the strong electric fields experienced under a Cumulonimbus. Since these ions would be of the opposite polarity to the charge of the cloud base and would increase in number with increased electric field, the rain drops they attach to would also be oppositely charged to the cloud base, but of proportionate magnitude. The mirror image effect has been verified by subsequent observations, including those using modern sensors and techniques (e.g. [15.56], [15.57]). Although the effect is generally observed, local sources of space-charge can partially mask the inverse correlation under certain circumstances [15.58]. Recent studies indicate that rain drop charge is highly responsive to the ambient electric field, changing within seconds of a field polarity reversal. This calls into question the traditional explanation of selective ion capture by the raindrops as being the primary cause of the mirror image effect [15.55], since a drop is unlikely to scavenge sufficient ions in ~1 s to significantly affect its charge [15.56].

Precipitation current instrumentation have been based on a conductor shielded from external electric fields by a grounded wire mesh and connected to a sensitive ammeter[15.56] [15.57] [15.59]. A funnel-shaped conductor has also been used ([15.56] and [15.57]), with an effective collection area of 0.2 m^2. This instrument did not contain any sharp protrusions to avoid contamination by corona discharge from strong electric fields during overhead thunderstorms. The current from the collector was logged at 50 Hz, with rainfall current, not individual drop charge, being reported. Rainfall intensity and drop size statistics were derived from a nearby distrometer. The direct measurement of precipitation current used by Simpson, and Soula and Chauzy, differs from the induction methods originally devised by [15.60] for measuring the terminal velocity of water drops in the laboratory and later applied to measuring size and charge of rain drops in the atmosphere ([15.61] [15.62]). The induction method requires the raindrop to pass through a loop conductor, where a current is induced and recorded by a sensitive ammeter. The drop charge is calculated from the induced current and has the advantage of preventing any effect of charge separation from drop breakup on the measurements [15.48].

As the number of charged rainfall observations increased throughout the 20th century, it was apparent that although the expectation of positive charge during the most intense part of the storm was generally observed, the polarity of convective rainfall can show considerable variability between different rainfall events. This may be due to variability in the strength of updrafts, which have been linked to the polarity associated with graupel, an important charge carrier and common source of rainfall in convective clouds [15.51]. The close association between updraft speed and cloud electrification (and therefore precipitation charge) has been established by theoretical and experiments studies (e.g. [15.63] [15.56] [15.64] [15.51]), with heavy rain showers with weak updrafts producing significantly less precipitation current than similarly intense showers containing stronger updrafts.

A further complication in the assessment of rainfall charge is the question of how representative the sampling site is to the spatial distribution of rainfall intensity of the storm. This becomes especially important for complex, multicellular convective systems, with localised anomalies in rainfall intensity or hail shafts being easily missed during its passage over a sampling site.

Snow electrification

Early research by [15.65] and [15.66] found that dry snowflakes were usually negatively charged, with rainfall and wet snow found to be generally positively charged. In both cases, increased precipitation rates produced large fluctuations in PG measured at the surface. Ice crystals below the -10°C isotherm height were reported by [15.51] to be of negative charge in the mature stage of a snow shower, with the graupel being positively charged. This is consistent with dry snowflakes reaching the surface with a negative charge. The polarity of ice crystals and graupel reversed at altitudes colder than -10°C.

Measurements of PG by [15.67] during a snow shower found that the PG increased during the heaviest portion of the shower, consistent with a lowering of negative charge to the surface by the snowflakes. Unlike during convective rainfall, the standard deviation of PG sampled at 1 Hz during the snow shower was low. [15.46] interpreted this as due primarily to the lower fall speed of the snowflakes, reducing short-period variability as the flakes moved slower past the sensor compared to raindrops, combined with a greater time for charge exchange with the air (and possibly each other), reducing the spatial and inter-flake charge variability.

As for sand and dust storms, wind-blown snow can acquire charge through triboelectrification, perturbing the fair-weather electric field at snow covered sites such as Antarctica [15.68].

15.3.4 Corona and point discharge

In strong electric fields, such as beneath thunderclouds, vertically-aligned rods and other objects may go in to corona, i.e. the air around the tip of the object may breakdown locally, allowing a large (microamp) current to flow. If the tip of the object is pointed, the electric field will be intensified and breakdown will occur under a smaller applied field. The current produced can extend over a wide range, so a logarithmic response current ammeter is appropriate (e.g. [15.69]). For atmospheric conditions, temperature compensation is usually required, or the possibility of comparison of two techniques [15.70].

15.4 Devices and Systems

Fair weather measurements seek to determine the conduction properties of air and the electric field, in the absence of local charge generation. The duration of fair weather conditions varies between sites, hence some durability is required for the apparatus to be continually available for when the fair weather circumstances arise.

15.4.1 Fair Weather devices and systems

For fair weather measurements, a typical atmospheric electricity station will include sensors and instruments for some or all of PG, air conductivity and vertical current density. The PG is commonly obtained with a field mill device, but its calibration depends on having another instrument for comparison. Often, a long wire (or *passive* wire, as there is no active method used to enhance its electrical coupling to the atmosphere) is used for this as it presents minimal distortion of the electric field. A passive wire works by acquiring the local potential of the air through collision of air ions, and falls into the general class of potential equaliser devices.

Potential equalisers

Measuring the local potential of air requires exchange of charge between a measurement electrode and the air around it, ideally as rapidly as possible. Methods used historically for this include the flame probe, in which the good electrical conductivity of a flame is used to enhance the charge exchange, and the Kelvin water dropper (see 15.2), which increases the area of charge collection by using a large number of small droplets. Radioactive potential equalisers are also effective in greatly increasing the local air conductivity and have been used extensively in the past, but are now rarely used because of the radiological hazard they present.

The long or passive wire antenna is probably the most commonly used potential equaliser. In its basic form, it consists of a thin uninsulated horizontal wire stretched at about one metre above the ground between insulators on two short masts (fig 15.4 and fig 15.5). The use of a thin wire and masts spaced well apart from each other ensures that the distortion of the atmospheric electric field is negligible, hence the passive wire provides a reference method for calibration. To operate satisfactorily, considerable attention must be given to the quality of the insulation at each end, in order that the leakage from the antenna is considerably less than the current flowing onto the antenna. [15.71] estimated that the requirement on the leakage current is that it is about 2 fA. With a potential difference across the insulator of typically 100 V, this is a very demanding requirement. However this can be achieved by using an additional insulator at each end with a short “guard” wire between the main insulator and secondary insulator. If this guard wire is driven to have a potential close to the measured potential (e.g. to within a few mV), the potential difference across the main insulator is greatly reduced, by a factor of $\sim 10^5$. This approach requires a wide range bipolar electrometer able to drive an external device to a measured potential, which the [15.22] and [15.71] designs implemented using thermionic valves, and for which the [15.23] design used transistors.

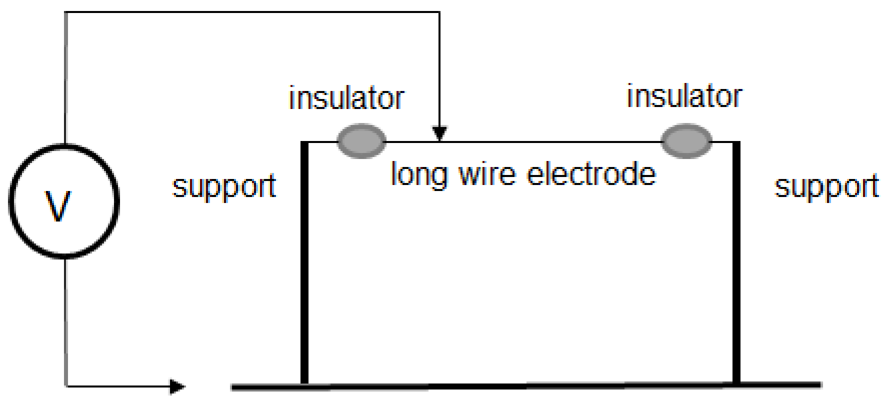

Fig 15.4. Passive wire antenna. A length of uninsulated wire is stretched between two support masts, using good quality insulators. The potential on the wire is measured using an electrometer voltmeter. (Typical dimensions: length of long wire 20m, support mast height 1m).

Fig 15.5. Passive wire apparatus showing the thin and long sensing wire emerging from a PTFE insulator. (Photo: A.J. Bennett).

Ion measurements

Measurements of atmospheric cluster ions typically operate using a deflecting electric field to collect the ions on an electrode, and the current flowing measured. If the rate of transport of air to the electrode is known, the number concentration of ions can be obtained, under the assumption that the ions are singly charged, due to the difficulty in bringing an additional charge to an existing polarised region around the ion. A cylindrical geometry is well suited to this approach (fig 15.6) e.g. following the design of *Hans Gerdien* (1877-1951), as the air can be driven along the cylinder mechanically, with a radial electric field applied to drive the ions to a central coaxial electrode.

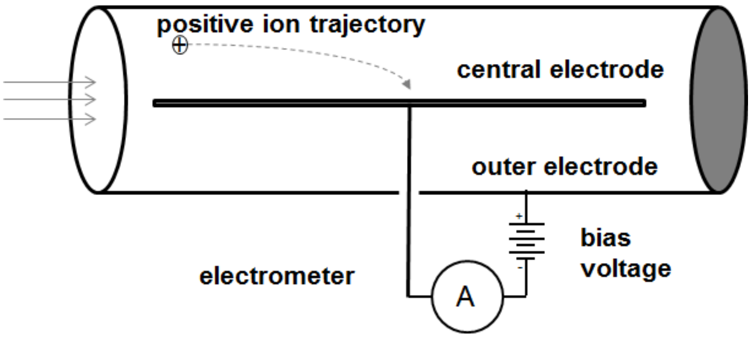

Fig 15.6. Concept of the operation of a cylindrical ion collector, with the outer electrode grounded. A bias voltage is used to establish a radial electric field. Ion-laden air is driven through the system, and ions are deflected by the electric field and collected at the central electrode, and the integrated current measured.

The bias voltage is chosen so that, for ions of the mobility required to be measured, an ion can be deflected to reach the central electrode within its transit time through the system. Ions with mobility less than the critical value determined by the electric field chosen will also be captured. By switching the polarity of the bias voltage, either positive or negative ions can be collected. There are many variations on the basic principle, for example using a sheath of air to define the capture distance more precisely, or by using a segmented electrode with a range of local electric fields.

The Programmable Ion Mobility Spectrometer or PIMS [15.72], allows a range of bias voltages to be programmed, to provide a sweep across the positive and negative ion mobility spectra (fig 15.7). From these, the bipolar ion concentrations can be determined. Continuous monitoring of the ion mobility spectrum can therefore be achieved. In this and many ion counters, it is necessary to compensate for temperature variations and the error currents from the impact of charged particles which is independent of the deflecting field applied.

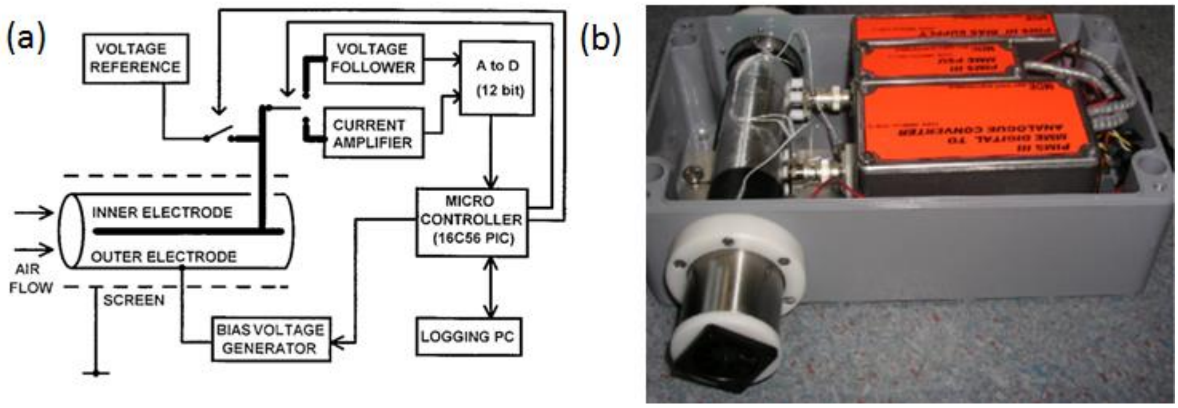

Fig 15.7. Programmable Ion Mobility Spectrometer (PIMS) of [15.72] shown in block diagram form (a), and physically (b). In (b), the fan providing the forced ventilation is at the foreground end of the cylindrical sampling electrodes on the left. ((a) from AIP, (b) Photo: R.G. Harrison).

Air conductivity

Air conductivity can be determined using charge relaxation methods or by direct ion counting and calculation. In the relaxation approach, the timescale τ of charging (or discharging) of an electrode exposed to air, is related to the total conductivity by$\tau = \varepsilon_0/\sigma$, where ε_0 is the permittivity of free space. Electrode configurations which have been used for this in the past include a passive wire, which is earthed and then allowed to acquire the local electric potential until it ceases to change, or the central electrode in an aspirated device. The classical device designed by Gerdien [15.14] used cylindrical geometry, a manually driven fan and a mechanical electrometer, for which the charge relaxation time was determined. The PIMS instrument can operate in both conduction and voltage decay modes, allowing internal consistency tests.

Good agreement has been found between a PIMS instrument used to determine the air conductivity by an ion counting method, and compared with the relaxation method for a passive wire antenna allowed to charge naturally [15.73] [15.74].

Current density

The most direct measurement of the air-Earth current density measurement requires the electrical isolation of a portion of the ground and apparatus to measure the current flow to Earth [15.27]. In reality, the isolated surface can be emulated by a conducting plate electrode mounted flush with flat, open ground so that the ambient electric field (and therefore air-Earth current) remains unaffected by the presence of the apparatus (fig 15.8). The balance between sensitivity and practicality requires that the surface area of this plate is normally between 0.1-1.0 m^2.

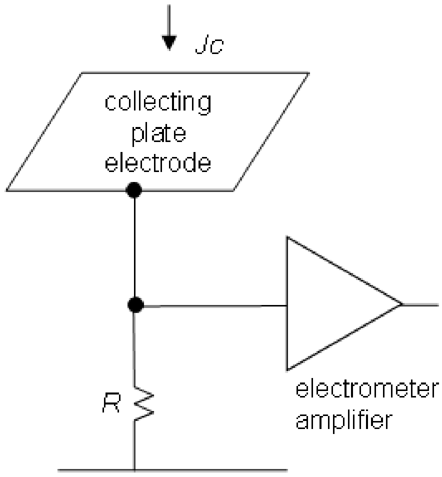

Fig 15.8. Concept of a plate electrode measurement for the vertical conduction current density. A horizontal plate is positioned slightly above the earth's surface on insulators, and the current flowing from it to the earth's surface measured.

A major challenge in continuous measurements of this current is the need to prevent leakage currents greater than a few tens of fA providing alternative conduction routes, especially during damp conditions. This requires high surface resistivity for all structures supporting the plate and the connection between the sensing electrode and the ammeter. Materials such as PTFE satisfy this requirement, although consideration must be made to the prevention of lower resistivity contaminants and moisture on the surface of the insulators. A guard ring surrounding the sensing electrode may also be used. The guard is electrically isolated from the sensing electrode it encloses, but held at the same voltage to prevent leakage currents [15.27] [15.75]. A temperature stable (or at least compensated) ammeter is required, sensitive to currents of order 10 fA, given the typical air-Earth current density of 1 pA m^{-2}. The current flowing can be measured by using a resistor to ground, but it is preferable to keep the plate itself at earth potential, which can be achieved using a transimpedance amplifier with a high value feedback resistor, usually in the gigaohm range. Depending on the required temporal sensitivity of the measurement, a parallel capacitor may be added to provide passive low pass smoothing.

During fair weather, precipitation and often turbulent components of the air-Earth current density are insignificant, leaving the conduction and displacement components. Whilst the displacement current density is of use when investigating lightning or local variability in the boundary layer, it is the conduction component that is of greatest importance for the study of the global electric circuit ([15.27]; [15.2]). As a consequence, air-Earth current density instrumentation need to eliminate or separate the displacement current component from conduction during fair weather. A method commonly used for continuous measurements due to its simplicity is to select the RC time constant of the sensor to that of the atmosphere (of order $1x10^3$s) as first described by [15.76]. This allows the displacement current to pass to ground through the capacitor, whilst the conduction current passes through the input resistor of the ammeter. Whilst simple to construct, a major disadvantage of this method is the required assumption of constant atmospheric relaxation time and therefore air conductivity. In reality, air conductivity varies significantly according to atmospheric aerosol concentration and ionisation rate. An alternative method which does not require this assumption is to use two different sensing electrodes of different geometry ([15.77] [15.73], fig 15.9. The magnitude of displacement current is proportional to the surface area of the electrode, whereas the predominantly vertically flowing conduction current is proportional to the electrode's horizontal cross sectional area. The conduction current component can therefore be isolated by subtracting the measurement made by two co-located electrodes of equal surface area but of unequal cross section.

In hostile conditions, it is important to ensure the insulation is maintained, which is particularly difficult if there is blowing snow. [15.78] developed a suspended spherical sensor which allowed the conduction current to flow into its upper hemisphere and out of the lower hemisphere. The electrometer circuit was entirely self-contained within the sphere.

Long wire (passive) antennas have also been used to measure the conduction current density, but the effective capture area must also be known, either by independent calibration or calculation (e.g. [15.79]).

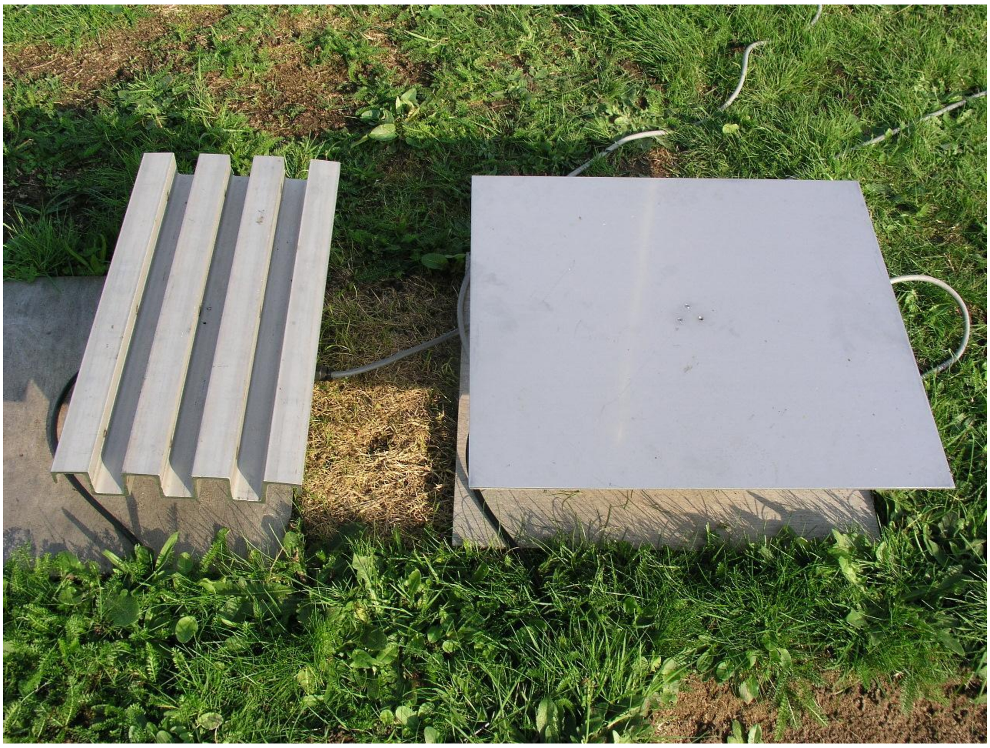

Fig 15.9. Measurement of the conduction and displacement current densities using the combined two electrodes of different geometry in a GDACCS instrument. (Photo: A.J. Bennett).

Electric field machines

“Electric field machines” represent a class of measuring devices that use motion of an electrode in some way to determine the electric field (fig 15.10). This approach is widely implemented in the electric field mill principle. A field mill operates by alternately exposing and covering an electrode, mechanically. As the electrode is exposed, the change in the electric field it encounters causes a charge to be induced. If the process is repeated rapidly, the current induced can be measured, which is related to the electric field to which the electrode is exposed. Furthermore, when the electrode is covered by the rotor, it is screened from the field and in a zero field environment. This gives a measure of the various offsets in the electronic system, which can be removed. Using a rotary geometry, a compact and durable instrument can be produced. Phase sensitive detection of the signal is usually employed, with the position of the rotor determined by optical or magnetic switches.

The induced current will be alternating at the frequency of the chopper’s exposure to the atmosphere, and the magnitude of the signal is proportional to the atmospheric electric field. The necessity for moving parts makes this instrument relatively high power compared to other sensors (few hundred mA from 12V supply for a rotating chopper) and subject to maintenance. The internal parts need to be kept electrically insulated as the induced current to be measured is very small (of order 1×10^{-12}A). The field mill will measure the DC electric field of the atmosphere and will be sensitive to all variability at frequencies lower than the chopping speed, which is usually ~200 Hz, although single rotations are normally averaged to reduce noise.

Fig 15.10. Designs of electric field mill: (left) Chilworth JCI131, (centre) Boltek EFM100, (right) Campbell CS110 (Photos: R.G. Harrison)

The alternate covering and uncovering of the sensing electrode (or stator) is achieved by mounting it beneath a rotating shielding electrode (or rotor), with sufficiently large gaps to prevent water from shorting out the electrode. The instrument can be used facing up or down. There are variations on the basic principle for specific applications, such as cylindrical electrodes rotating around an axis for dust sampling, or rotating sampling spheres for use on balloons in thunderstorms, to minimise instrument corona effects. Durability is improved by modern brushless design [15.80].

15.4.2 Disturbed Weather Systems

Methods for remote lightning detection developed during the later twentieth century, which, through the use of networked systems, allowed the rapid dissemination of information about storm systems. Because a single sensor can detect remote lighting sources, and monitor even greater areas in the case of satellite-carried instruments, regional lightning detection systems can be implemented relatively cheaply.

Meteorological services

Almost all national meteorological services implement lightning detection networks or have access to the data provided by them. Forecasters find the additional information about convective storms useful, as the presence of lightning identifies active convection. For some specific circumstances, notably in Iceland, detection of lightning may provide the first information about the existence of an eruption plume from a volcano.

Stand-alone warning systems

Where a situation requires local thunderstorm detection without the need for an internet connection or data provided by a third party, single site, stand-alone warning systems are available. Aside from human observation, commercial stand-alone detectors use either radio or (quasi) electrostatic techniques, sometimes combined with an optical receiver.

Lightning is detected mainly by the strong radio-frequency pulse produced by the lightning channel. The pulse covers the entire radio frequency (RF), but has a peak emission at approximately 10 kHz in the Very Low Frequency (VLF) part of the spectrum. Depending on the frequency chosen, a RF detector may be bias to reporting only cloud-to-ground lightning flashes. A stand-alone RF detector will need to recognise the lightning pulse from background noise so usually incorporates either crude filtering or a microprocessor to distinguish characteristics of the signal such as pulse length, rise time etc. The bearing of the emission can be reported using a magnetic induction loop. The simplest RF detectors simply report a suspected lightning pulse and use the signal-to-noise ratio, pulse characteristics or dual frequency input to estimate the distance to the strike, with no information on bearing. The trend of lightning pulse amplitudes is used to estimate whether the storm is approaching or retreating. These sensors are generally inexpensive and highly portable, although of varied performance. Lightning flash distance estimates using a single site, stand-alone RF sensor are inherently inaccurate due to the natural variability of lightning peak currents and the power falling by only the inverse, or at best square, of distance. Pulse analysis and/or dual antennas of different frequency response provides an improvement to range estimation based on RF amplitude alone.

Sensors which incorporate orthogonal magnetic field antennas to estimate strike bearing from the site generally provide a reasonable estimate of bearing providing they are located away from strong magnetic field/ferrous sources or not in complex terrain which can distort the magnetic field of the signal. When magnetic direction finding from a single sensor is combined with the inaccurate distance estimates, the resultant storm location on the map tends to be scattered along the bearing line, making storm location from a single RF sensor rather ambiguous in these situations. RF sensors will always be subject to anthropogenic noise common in the radio spectrum, even down to VLF.

Sources of noise originating from sparks from electric motors, power transmission, transportation etc. are particularly troublesome as they can display similar characteristics to a lightning pulse, or raise the noise floor to an unacceptable level. Lightning detectors measuring the magnetic field component (most commonly used) have the advantage that they can operate indoors and when covered, but may be more subject to anthropogenic noise as the magnetic component of the electromagnetic radiation will penetrate building walls more effectively than the electric field component. Even the signal from nearby computers and mobile phones has been found to produce false-alarms in simple stand-alone RF detectors. Their key advantages over other systems are often related to price, ease of use and portability rather than performance.

Electrostatic lightning detection is defined here as any measurement technique using variability in the atmospheric electric field below 100 Hz, where the electromagnetic component of local lightning emission is small compared to the amplitude of the electrostatically generated field change. An electric field change resulting from lightning is the oldest method of quantitative lightning and thunderstorm electrification determination (e.g. [15.27]; [15.17]), with its use in thunderstorm research and warning still used in the twenty-first century (e.g. [15.45]; [15.81]). Stand-alone electrostatic methods exploit the large and rapid change in electric field produced by rapid transfer of charge by nearby lightning. The electric field is usually measured by an electric field mill. Except for very close flashes (within 5 km) the signal requires careful interpretation to detect a lightning flash since lightning signals can appear similar to non-lightning sources of variability such as charged precipitation or even birds flying close by. Electric field mills can be combined with co-located sensors using a different method (e.g. optical) to verify the presence of lightning. As the electric field mill needs to be exposed to the atmosphere, it can only be installed where there is a clear view of the overhead sky (e.g. no overhanging tree branches, cables etc.) and as far from taller objects as possible, as these will distort the electric field. Electric field mills are capable of detecting lightning to approximately 40 km, depending on their sensitivity, background noise at the site and the lightning strength. This sensor will not be able to detect the bearing of the lightning, but when calibrated and sampled at a rate of at least 10 Hz will provide a greatly superior indication of distance to the strike compared to a single RF sensor using amplitude alone, as the electrostatic signal reduces by the inverse of the distance cubed. The primary use of an electric field mill is normally to warn of an increased DC atmospheric electric field magnitude indicative of electrified cloud overhead (e.g. [15.83], rather than the detection and range of lightning itself.

An alternative to measuring the DC or slow-varying electrostatic field for stand-alone local thunderstorm detection is to use a displacement current sensor. These sensors work on a similar principle to the chopper in an electric field mill, where a current is induced in a conductor due to the variation of an electric field. Unlike the field mill however, the sensor does not record the DC electric field, but only the changes, so is in this respect the same as a radio receiver and does not require any moving parts. By constructing an antenna and suitable filtering to enable only changes in the atmospheric electric field resulting from lightning to be recorded (e.g. approximately 1-100 Hz) and avoiding the frequencies associated with the RF component of the discharge and artificial transmitters (>1000 Hz) it is possible to produce an instrument which does not require the moving parts and unwanted slow variability of the DC field characteristic of a field mill yet still retains the ability to detect the electrostatic change associated with a lightning strike [15.20], fig 15.11. Like the field mill, only distance to the flash can be derived, but again with a much greater sensitivity than RF due to the inverse distance cubed relation for electrostatic signals. A displacement current detector sampling between ~1-50 Hz can also detect charged precipitation and the increased electric field variability produced by the production of corona ions during the strong electric field beneath a thunderstorm ([15.20] [15.81]). Both signals can be used to warn of increased potential for overhead lightning activity. Like field mills, single-site displacement-type detectors cannot be used indoors, are not usually highly portable, their electrodes require good electrical insulation from the ground to be maintained and they cannot provide flash bearing (fig 15.12). Unlike their RF counterparts they are more resistant to false alarms, very sensitive to all types of local flashes and able to detect non-lightning signals such as charged precipitation, which can be used to warn of potential nearby cloud electrification before the first lightning flash has occurred. A summary of the advantages and disadvantages of these detection methods is presented in Table 15.2.

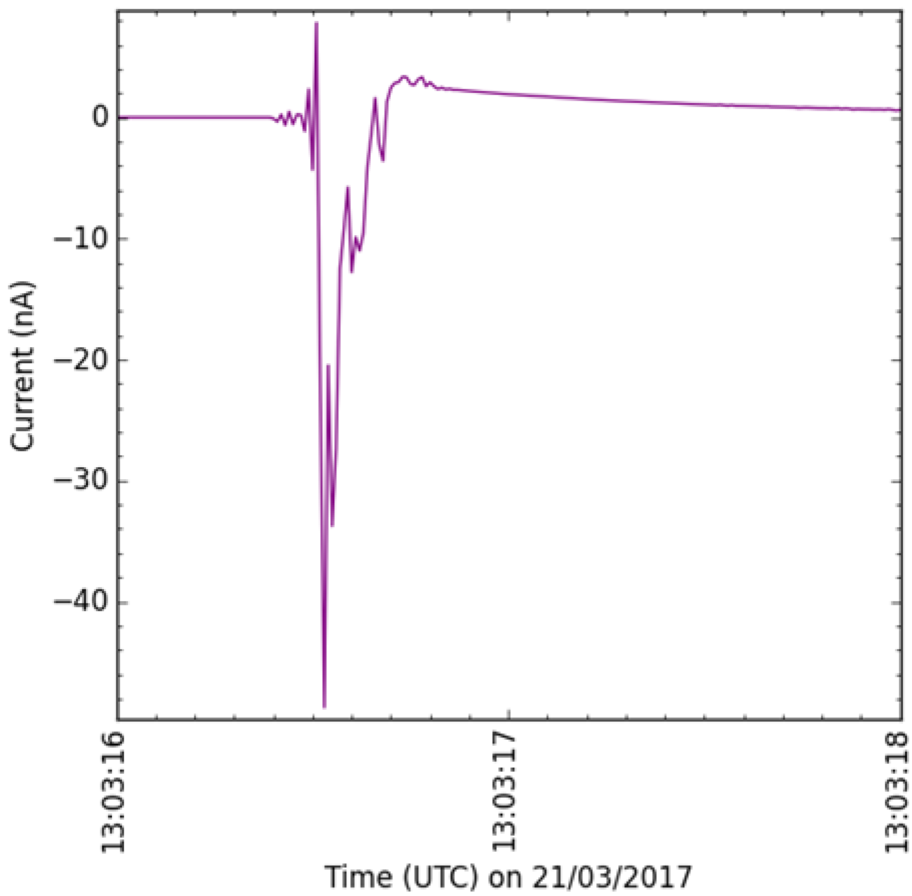

Fig 15.11. Displacement current induced on the electrode of a BTD-300 thunderstorm detector by a lightning flash approximately 20 km away.

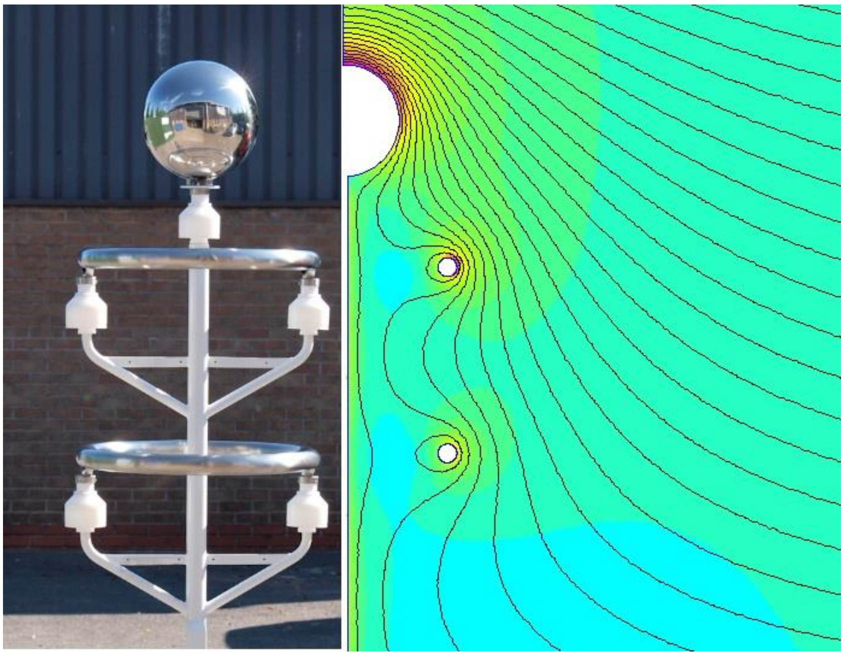

Fig 15.12 The Biral BTD-300 thunderstorm detector, with modelled lines of equipotential (black) compared to ground and electric field magnitude (colours) surrounding the three stainless-steel sensing electrodes. Warmer colours denote stronger field. (Photo and model: A. J. Bennett).

Technique	Advantages	Disadvantages
RF network	Excellent location accuracy (to few 100m) and good detection efficiency if network sufficiently dense. Sensor redundancy. Flash type and polarity discrimination. Can provide national or even global coverage.	Expensive to install and maintain. Requires multiple sites, sometimes in different countries. Method of rapid, long-range communication and central processing needed. Can only detect hazard after lightning is produced.
RF standalone	Only one sensor and site required. Can have good detection efficiency. Same signal used for range and direction. User-owned and operated.	False alarm rate can be high due to anthropogenic radio interference. Range accuracy can be poor, depending on method. Using VLF only can limit intra-cloud stroke detection efficiency. Can only detect hazard after lightning is produced.
Displacement current (<50 Hz)	Only one sensor and site required. Very good flash detection efficiency within 100 km. User-owned and operated. Operates below most anthropogenic noise sources. Can warn of strongly charged cloud overhead before the first	Difficult to determine flash type. Requires exposure to the atmosphere whilst maintaining robust electrical insulation. Range accuracy low compared to RF network. Range limit of ~100 km.

	flash occurs.	
Field mill	Only one sensor and site required. Very good flash detection efficiency within 10 km. User-owned and operated. Operates below most anthropogenic noise sources. Can warn of strongly charged cloud overhead before the first flash occurs. Quantifies DC field so can also be used for fair-weather atmospheric electrical monitoring.	Cannot determine flash type. Contains moving parts so liable to mechanical failure. Output can be difficult to interpret due to several sources of atmospheric field change during precipitation. Short range (~30 km for lightning) and usually unsuitable for flash range determination beyond "near" and "far".

Table 15.2: Comparison of different disturbed weather detection techniques.

15.5 Specifications

In this section, the typical accuracies and connections for the different instruments are discussed.

15.5.1 Fair weather requirements

Generally, the fair weather PG is about 100 Vm^{-1} and accurate measurements are possible to a few Vm^{-1}, with a dynamic range of ± 500 Vm^{-1} usually desirable to allow non-fair weather data to be identified. However, the limitation on fair weather data is largely that of the local environmental circumstances exposure, as surface PG is strongly affected by local meteorological conditions. If the object of the measurements is to obtain globally-relevant information rather than local, the data has to be selected for that arising under undisturbed conditions. The conventional approach to this is to use data obtained under so-called "fair weather" conditions, during which there are regarded to be no local sources of electrical disturbance.

15.5.2 Automatic recording

Typical modern field mill instruments provide an analogue output voltage or direct digital data (e.g. via a serial protocol such as RS232 or RS422 or Ethernet). This means that they can be used straightforwardly with data loggers. For fair weather data, sampling rates of 1 s are adequate, with averages computed at 1 minute or 5 minute.

15.5.3 Disturbed Weather requirements

For the detection of strong atmospheric electric fields associated with disturbed weather conditions, it is necessary to measure the DC electrostatic field change of magnitude exceeding approximately 500 Vm^{-1}, with an upper limit of at least 10 kVm^{-1}, ideally 100 kV^{-1}, with a resolution and measurement uncertainty of at least 100 Vm^{-1}, if quantification of the field is required. Alternatively, detection of electrical changes characteristic of strong electric field conditions such as strongly charged precipitation (hydrometeors with individual charges typically in excess of 10 pC) and rapid electric field variability associated with wind-blown space charge (of order 10 (Vm^{-1})s^{-1} or more) or nearby lightning flashes (usually exceeding 1000 (Vm^{-1})s^{-1}). As for fair weather measurements, sampling rates of 1 s are acceptable for disturbed weather monitoring, with sampling rate of at least 20Hz required to adequately capture electrostatic field changes associated with lightning flashes, using a field mill or displacement current sensor. Radio detection of lightning normally starts at VLF (3-30 kHz) for long-range (>1000 km), predominately cloud-to-ground strokes, to LF and above (realistically >100 kHz) to ensure reasonable detection efficiency of weaker intra-cloud strokes at ranges exceeding a few 100 km.

15.6 Quality control

As with all instruments, the quality of the measurement has to be considered before they are used for a scientific analysis. This has to address the exposure of the instrument, and an assessment made of the validity of the results obtained.

15.6.1 Fair Weather

Depending on the climatology of the site concerned, fair weather circumstances will generally only occur intermittently. The classification of the meteorological conditions is therefore an important consideration in determining which measurements to retain for further analysis. For accurate measurement of the electric field, calibration of the installation is required, through a combination of sensor characterisation and knowledge of the correction factors to be applied to represent any local distortion of the electric field.

Reduction factor for electric field

When a field mill or other measuring device is installed on a mast, the local electric field encountered will be distorted (fig 15.13). This affects the measurements, usually enhancing the field measured. It is necessary to determine a calibration for the each installation individually, to allow it to be corrected (or *reduced*) to that of an open flat site with the measurement made flush with the surface. Determining the “reduction factor” to correct the measurements to that of an open surface is therefore required. This is achieved by comparison with a calibration measurement which is not affected by distortion, or, theoretically, by using an electrostatic model of the installation in which the distortion can be calculated.

The principle of the experimental approach to this is to run a second set of calibration measurements simultaneously in an undistorted situation, and derive the ratio between the two instruments during the same interval, which need not be very long (~ minutes to hours) as long as the two instruments show well correlated values.

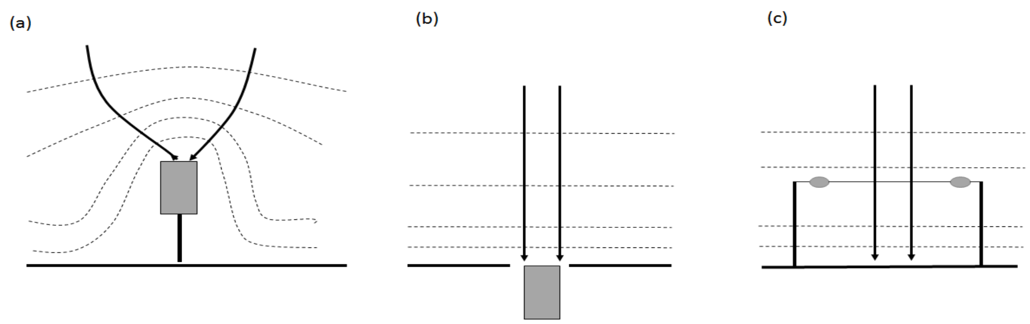

Fig 15.13. (a)Distortion of the electric field (solid lines, with dashed lines showing equipotentials) for a measuring instrument mounted on a vertical mast. (b) Removal of the electric field distortion by burying the instrument in the ground, with its sensing aperture flush with the ground. (c) A passive wire potential measurement is negligibly affected by the distortion effects. (From [15.84])

One option to remove the distortion is to mount the calibrating instrument so that it is flush with the ground; another is to compare it with a passive wire antenna, which shows negligible distortion of the field because of its small geometry.

Conductivity from relaxation

The air conductivity at the surface is typically in the range of 2 fS m^{-1} to 30 fS m^{-1}. To establish if an air conductivity measurement is reliable, it should be compared with that from another instrument, or by using a combination of techniques allowing a consistency check. The PIMS instrument, for example, can operate as a relaxation device as well as a current measurement device, allowing self-consistency checks ([15.72]). It is also possible to compare two different techniques, e.g. the comparison of conductivity from an ion counter instrument, with that derived from the relaxation time of a passive wire system ([15.73]).

Removal of power line interference

With sensitive electrometers connected to exposed electrodes there can be difficulties with power line interference. This can be very local, and vary with time of day depending on the loading of the power grid. Corona ions can be generated from breakdown of high voltage power lines and provide a direct source of interfering ions. For atmospheric electricity applications, when full screening is, almost by definition, impossible, it may be necessary to move the instruments to an electrically quieter site, or one in which saturation of the instruments by power line noise is sufficiently reduced that other filtering techniques become possible. Active compensation of power line interference at 50 Hz has been found to provide some improvements for an exposed plate electrode ([15.25]), including embedded sharp digital FIR filtering stages to produce a low-pass filter below 50 Hz, such as that used by the Biral BTD-300.

Identification of Fair Weather

The selection of fair weather conditions is important in establishing which measurements are suitable for comparison with those from other sites. Various criteria have historically been used to identify fair weather conditions, but those of the UK Met Office (UKMO) originating in the 1950s have established themselves as capable of providing data in which global signals have been detected. The original UKMO criteria[85] for fair weather were:

(1) the absence of hydrometeors

(2) no low stratus cloud

(3) less than three-eighths cumuliform cloud

(4) a mean hourly wind speed of less than 8 ms^{-1}.

The UKMO applied these criteria on an hour by hour basis, to designate hourly PG data values as having "no hydrometeors" (i.e. no rain, hail or snow), or being "fair weather" (OYB, 1964). Daily and monthly averages were constructed from these hours.

Some refinements to these criteria have been suggested by [15.84], to make use of modern automatic measurement systems. These refinements are to ensure that the visual range exceeds 2 km, that no extensive stratus cloud with cloud base below 1500 m is present, and that the surface wind speed is between 1 ms^{-1} and 8 ms^{-1}. Taken together with original UKMO requirements, the revised fair criteria are:

(FW1) no hydrometeors, aerosol and haze, as apparent from the visual range exceeding 2 km

(FW2) negligible cumuliform cloud and no extensive stratus cloud with cloud base below 1500 m,
(FW3) surface wind speed between 1 m s^{-1} and 8 m s^{-1}

This overall selection approach of identifying fair weather hours can now be implemented using automatic meteorological instrumentation at the same site. It has the merit over daily data selection, that, even if the weather is disturbed at a particular site, it is still possible to make the best use of the available values in forming climatological values.

15.6.2 Disturbed Weather quality control

Instruments used for disturbed weather measurements typically require less maintenance than for fair weather measurements, as the signals detected are usually larger. Nevertheless, there are quality and reliability considerations for accurate and consistent measurements to be obtained.

Detection efficiency

The detection efficiency (probability of detection) of a lightning detection system quantifies the amount of lightning activity within a given geographical area which is expected to be detected by the system. The detection efficiency is normally expressed as a percentage and can relate to either lightning strokes or flashes, depending on the technology used. The detection efficiency (DE) is a function of receiver sensitivity, noise, lightning strength and distance. It is therefore common to relate DE to a lower threshold of peak current, type (CG or IC/CC), geographical area (for a lightning location network), or as a function of proximity to individual stand-alone detectors. Reliable "ground truth" data against which to determine the absolute DE of a system is challenging to obtain, given the challenge of detecting all lightning flashes in a known region during a comparison. The use of video evidence of lightning affecting known locations, lightning damage records and short range, high sensitivity VHF mapping arrays are examples of previously used methods to estimate DE from independent observations. Such independent verification has its limitations, especially with respect to weaker intra-cloud flashes, so DE relative to a high-performance lightning location network is sometimes quoted instead of absolute ground truth data. High-performance VLF/LF networks typically quote a DE of >95% in their network centre for CG flashes with peak currents exceeding a few kA.

False alarm rate

The false alarm rate (FAR), also known as the probability of false detection (POFD), of a lightning detection system is commonly expressed as a percentage of cases where an event is falsely detected compared to the total number of strokes or flashes. The false alarm rate is therefore sometimes confused with what is more properly determined as the false alarm ratio, since correct negatives are not accounted for. The FAR can also be expressed in terms of false alarms per unit of time (e.g. false alarms per day), which is more likely to be the correct determination of FAR but requires an appropriate time interval to be determined. Like DE, determination of absolute “ground truth” FAR is difficult to obtain due to lack of a reliable method of detecting every electrical discharge affecting an area. False alarm expectations quoted by manufacturers and operators of lightning detection systems are usually less than 2%, although it can be unclear whether the value relates to POFD or false alarm ratio.

15.7 Maintenance

The operation of atmospheric electricity equipment, requires regular attendance and maintenance, depending on the environmental conditions encountered (see also Table 15.2). Snow and ice, when present, must be removed if the apparatus is not specifically designed for those conditions.

15.7.1 Fair Weather maintenance

Operation of fair weather equipment is particular demanding, because of the great sensitivity of the instruments to leakage and degradation

Insulators and insulation

Due to the often pico-ampere currents and high impedances involved in the measurement of fair weather atmospheric electrical parameters, robust, highly resistive insulation is essential. The material used for insulation varies with application and availability, from amber, sulphur and even heated sapphire in early twentieth century instrumentation, to Polytetrafluoroethylene (PTFE) for modern instrumentation. PTFE has many desirable properties for this purpose, including very high surface resistivity, hydrophobic with low water absorption rate, low chemical and UV reactivity, resistance to residue accumulation as well as being relatively inexpensive, mechanically robust (aside for creep under pressure) and easy to machine. Nonetheless, if an insulator is to operate reliably when exposed to environmental conditions, slight heating of the surface is normally required to prevent a lowering of surface resistivity in damp conditions, especially when hygroscopic impurities inevitably accumulate on exposed surfaces. The heat source can be placed inside the insulator, warming the surface from the inside (fig 15.14). However, as with other plastics, PTFE is a poor thermal conductor so heater power and material thickness need to be considered to ensure effective surface heating. A rain shield can also be used to physically prevent precipitation from wetting the insulator, which would not be evaporated in sufficient time. Spider webs have always been a problem for very high impedance measurements such as air-Earth current density, since they can introduce leakage currents to the sensing electrode when damp. There is currently no clearly successful method of preventing spider web accumulation on sensors, so instrumentation and fieldwork should be designed to minimise this risk. Maintenance for well-designed insulators is normally light, with the occasional (perhaps six-monthly) check on heater effectiveness and removal of any spider webs and surface impurities.

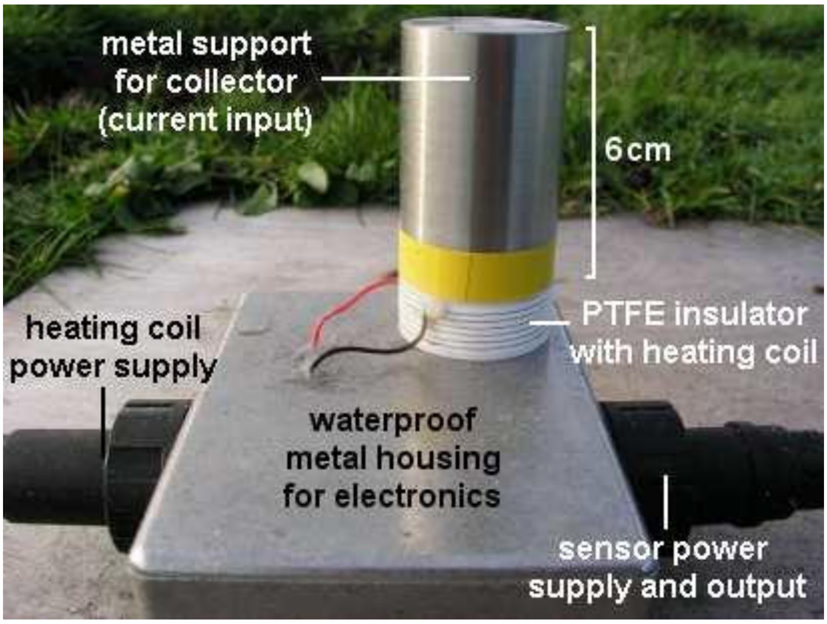

Fig 15.14. Heated PTFE insulation of the Geometrical Displacement and Conduction Current Sensor (GDACCS). Ultra-high quality insulation is required continuously between the sensing electrode and ground. (From [15.46])

15.7.2 Disturbed weather maintenance

Electrostatic lightning detection instrumentation will have similar insulation requirements of their sensing electrode to those of fair weather equipment (fig 15.15). The moving parts of field mill-type electrostatic sensors are subject to mechanical wear and jamming from foreign objects entering the chopper exposure slots. Initial start-up may also be problematic in sub-zero temperature or heavily contaminated environments if the chopper or motor becomes stuck. Ensure the mechanism moves freely, is free from foreign objects (including insects) and there are no objects preventing the chopper from being fully exposed to the atmosphere through the slots (e.g. by leaves, snow accumulation or excessive coverage of spider webs).

For optical lightning detection, a primary requirement is that the optical window remains free from obscuration by opaque material (e.g. leaf debris, snow, mud and spiders webs) and gradual reduction of transmittance from accumulation of surface contaminants, including salt and algal growth. Dew and frost on the window will also reduce the window transmittance and therefore sensitivity to a lightning signal.

Lightning detection based on radio (RF) signals will generally require less maintenance than instrumentation requiring moving parts and fully exposed electrodes (since the electromagnetic radiation is not greatly affected by electrically resistive weather shielding). The background noise should be periodically monitored for any significant increase in noise sources which may obscure or distort the lightning signals. If an increase in noise is detected, the addition of software-defined notch filters can be used to attenuate narrowband noise sources in the listening frequency such as communication transmitters. Broadband noise sources such as sparking of electrical equipment are best avoided during site selection. Electrical shielding of the sensitive (pre-amplified) parts of the receiver electronics will reduce noise issues, such as shielded coaxial cable and grounded, metallic shielding on circuit boards. Note that even if a receiver is designed for low frequency signals, the geometry of the pre-amplified circuit board tracks may still permit significant interference from microwave signals if left unshielded. It is also important to maintain a good electrical ground on the RF receiving equipment for best performance, which may involve deep ground spikes for sites with low ground conductivity. Appropriate electrical impedance must be maintained for the antenna assembly and RF cabling, to keep the standing wave ratio (SWR) as close to unity as possible, optimising the power transfer. For VHF phase-sensitive radio detection (e.g. interferometry), relative cable length is an especially important consideration, with the short wavelengths involved requiring the maintenance of correctly matched cables to avoid errors in phase shift calculation.

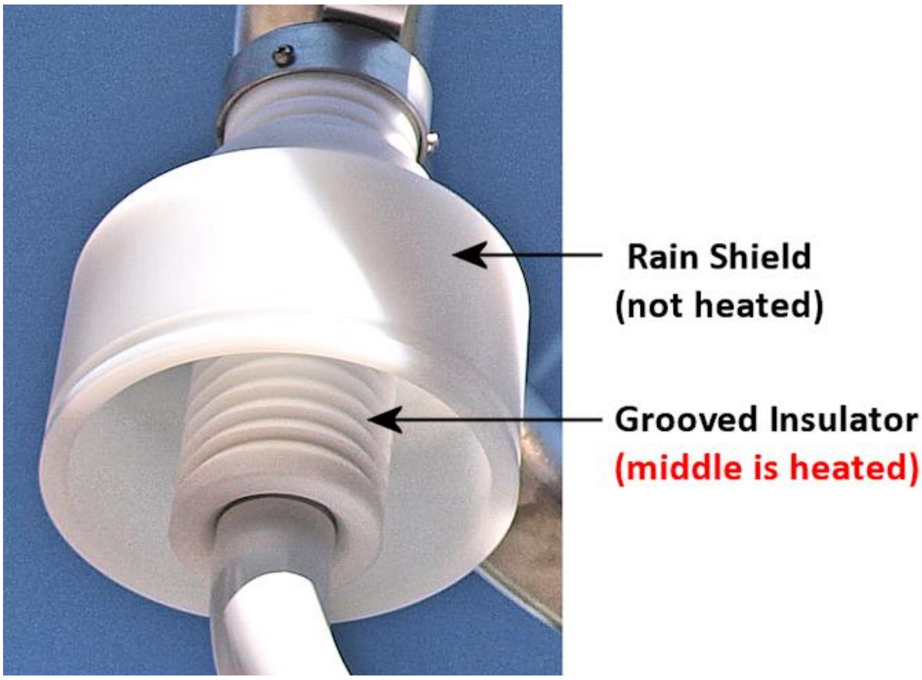

Fig 15.15. Electrical isolation method for the sensing electrode of a Biral BTD-300 thunderstorm detector, showing the shielded and heated PTFE insulator to prevent water-induced grounding during all weather conditions. (Photo: A.J. Bennett)

Table 15.2 Maintenance schedule of instrumentation at mid-latitudes

Maintenance interval	**Air conductivity sampling tubes**	**Plate electrodes**	**Field Mill**	**Electrostatic lightning detection**

daily	Surface cleaning and drying of insulators	Debris removal and drying of insulators		
weekly	Partial dismantling and cleaning of insulators	Clear plants growing near electrodes	Inspect for dead insects	
annual	Replace insulators. Rebuild and recalibrate	Rebuild electrometer	Clean and rebuild if necessary	Surface cleaning of insulators. Test and recalibrate

15.8 Applications

Surface atmospheric electricity measurements have a wide range of applications including detecting charged clouds over head and providing lightning warnings.

Atmospheric electricity measurements span a wide parameter space, and accordingly have many uses. The fair weather measurements are chiefly used for studies of the atmosphere's global electric circuit, through which current flows from tropical disturbed weather regions around the planet. It is particularly influenced by space weather and pollution. Space weather variations and their effects are an active area of study, which the atmospheric electricity data complements. In particular, the possible solar-terrestrial coupling mechanisms with the lower atmosphere can be explored, through, for example, electrical effects in fair weather clouds (fig 15.16). Effects of pollution are also sensitively apparent in the air conductivity: aerosol pollution decreases the air conductivity, and releases of radioactivity increase the air conductivity. There are associated effects on the Potential Gradient, with a sharp decrease associated with radioactivity and a steady increase with increased aerosol pollution. Disturbed weather effects, principally the detection of lightning, have immediate applications to weather forecasting and aviation meteorology.

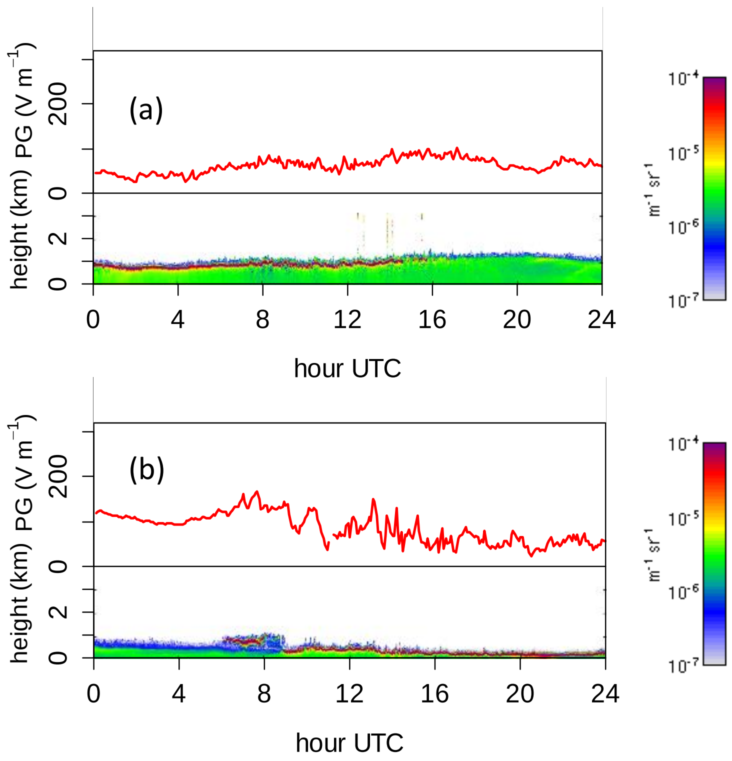

Fig 15.16. Potential Gradient (upper panels, red trace) measured under low stratiform cloud at Reading, observed using a co-located JCI131 field mill and Vaisala CL31 ceilometer (lower panels). (a) Effect of low cloud on the variability in the surface PG on 9th May 2017, showing the coupling between the cloud base charge and the PG which ceases when the cloud dissipates at about 16UTC. (b) Cloud base charge effect on the surface PG on 15th March 2016, which leads to a reduction in the PG as the negative charge in the cloud base is brought nearer to the surface with reducing cloud base height. (Ceilometer data are coloured by the backscatter generated according to the colour bar, the cloud base itself yielding the red colour.)

15.9 Future Developments

Continued miniaturisation of atmospheric electricity sensors makes measurements possible on airborne platforms, such as weather balloons and Unmanned Aerial Vehicles (UAVs). This will allow investigation of the electrical environment within a range of clouds, and, further, regular measurements of the vertical profile of the electric field under fair weather conditions. The vertical integral of the electric field, known as the ionospheric potential, represents a global circuit parameter which has previously been difficult to monitor with continuity beyond that of individual investigators or projects. Improvements to the design of all-weather electrical insulation and cheaper, faster processors will allow more sophisticated and smaller sensors for electrostatic thunderstorm detection. Improved digital storage capacity combined with greater processing speed will permit lightning monitoring including raw data logging at higher frequencies, thereby capturing smaller and weaker components of electrical discharge. Continued characterisation of the electrical conditions prior to lightning activity will be required to produce robust, reliable pre-flash warning devices, with associated benefits to lightning safety. Reduced price and increased sensitivity of CCD cameras and photomultipliers can widen the participation of Transient Luminous Events (TLEs) monitoring, with more numerous, detailed and full-colour images of TLEs available across broader regions of the world. The advancement of near-global lightning and TLE monitoring from space will provide a significant addition to ground-based detection methods, especially for weak intra-cloud activity over the oceans.

Further reading

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