Electrical current along balloon rigging line inside thunderstorms

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Abstract

We have designed a new instrument to measure the current flowing along balloon rigging line during flights through thunderstorms. This instrument was tested in a high voltage facility and used to collect line current data during one balloon flight into a thunderstorm. Using these data, worst-case calculations are made; as such, we claim that they are the upper limits of any alteration (to the measured electric field or particle charge) that may occur, and the real number is likely much less. It is postulated the rigging-line current could have two separate effects on the measured electric field: (1) reduction of the field due to emission of corona ions, and (2) enhancement of the field due to the insertion of a long thin ‘conductor.’ Even with current as high as 1 μA (the largest measured was around 50–100 nA), these two effects were found to be about −1% and +1%, respectively. Also, the calculated worst-case alteration to charged precipitation measurements is about 0.1 pC. Thus, with proper efforts to make the rigging line as poor a conductor as possible, it seems that we are justified in stating that these effects are negligible. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

For nearly a century now, scientists have been making atmospheric electricity measurements with instrumented balloons. Most of these measurements had the follow-
ing things in common: an envelope filled with some light gas that lifts a measuring device upwards through the atmosphere. Necessarily, the measuring equipment is connected to the envelope with some type of rigging line. Our research focuses on measuring the electrical properties inside thunderstorms, an extremely hostile environment to instrumentation for many reasons. This paper is concerned with two of those reasons: high electric fields and moderate to high liquid water contents. It turns out that under these conditions, nylon monofilament rigging line can carry an electrical current.

Jonsson (1990) took pieces of nylon monofilament rigging line, wetted them, and connected them to a power supply, forcing an electrical current to flow in the line. Jonsson suggested that the same thing might be occurring during balloon flights and wondered what effect this leakage current might have on the electrical measurements. Note that the rigging line measurements presented by Jonsson were made in a laboratory, using a method that was very different from what happens to our balloon train inside a thunderstorm. Nevertheless, we were compelled to find out what, if any, relationship these laboratory measurements had with what happens to rigging line during a balloon flight. An instrument has now been designed, tested in a high voltage facility, and used to measure real rigging-line current during one balloon flight into a thunderstorm.

2. Instrumentation

For the past two decades, our primary rigging line has been nylon monofilament, 1.5–2.0 mm in diameter. Beginning in 1990, we have treated our monofilament lines with water repellant coatings—a mixture of DuPont’s Nalan® W and Zepel®. Jonsson (1990) reported that the coated monofilament exhibited an order of magnitude reduction in leakage current when compared with uncoated line. He also tested another type of line we had used occasionally, which is made from small nylon fibers that are braided and coated with wax—also referred to as lacing cord. He found that this line exhibited an order of magnitude less current than coated monofilament. Based on these results, we altered our balloon rigging in the following way: within 1 m of the electric field meter or particle charge sensor, waxed nylon line is used; farther away, where extra strength is required, the coated nylon monofilament line is used.

The balloon train in Fig. 1 shows the four instruments used. Nearest the balloon are two Vaisala radiosondes: one is an RS80-15L that uses LORAN for tracking and the other is an RS80-15G that uses GPS. These sondes were tracked by an M-CLASS system (Rust et al., 1990) and a Vaisala Digi-CORA-II MW15 groundstation, respectively. Next is the line current sensor, described below. At the bottom is the electric field meter (EFM), which measures the strength of the electric field. Details of the electric field meter can be found in Winn et al. (1978) and Marshall et al. (1995).

The physical package and line attachment of the line current sensor are shown in Fig. 2. The current flowing in coated monofilament line is measured by wrapping wires around the line in two places, separated by a dry section of line (where it passes through a Teflon® support). This prevents the wires from being shorted by a water coating. The
Fig. 1. The instrument train used to collect the line current data. Near the top of the train are the radiosondes: a LORAN tracking sonde and a GPS sonde, both of which provide atmospheric pressure, temperature, humidity, horizontal winds, and three-dimensional position. About 3 m from the tail of the balloon is the line current instrument, which measures currents flowing along the rigging line. At the bottom is the electric field meter (EFM), from which the components of the electric vector can be determined. The let-down reel contains about 10 m of line.

The instrument provides a low-impedance path for current, creating a current divider where nearly all of the line current flows through the instrument. To help increase the corona threshold of the sharp, bare wire ends that attach to the nylon line, two things were done. First, brass spheres (12.7 mm diameter) are used to cover the bare end of the wire where it wraps around the line. These spheres are held in place by a bit of RTV silicone sealer around the bottom of each sphere. Second, the attachment section of line is surrounded with a shielding cylinder (aluminum, 7 cm diameter, 33 cm tall). This cylinder is centered on the line with Teflon spacers and the sharp upper and lower ends are covered with Tygon tubing to increase its corona threshold. Tests in the Langmuir Lab high voltage facility, which is at an atmospheric pressure of about 70 kPa, showed that without the shielding cylinder, the instrument would measure current when dry, meaning
that it was measuring its own corona current. The shielding cylinder solved this
problem, and as flown, the instrument did not measure current in dry line up to an
electric field strength of 125 kV/m (the largest field strength tested). The shielding cylinder is open at the top and bottom so that the line will be subjected to the cloud environment.

The measuring circuit is a simple operational amplifier (op-amp) integrator (see Fig. 3). To help remove noise caused by the telemetry transmitter, a 400-MHz filter is used at the inputs of the integrator. We are interested in measuring steady current flow, not lightning transients or corona bursts, so the output of the integrator was low-pass filtered. The op-amp used is an Advanced Linear Device’s ALD1701, chosen for two reasons: (1) low bias current (1 pA), which is important so that the op-amp does not significantly charge the capacitor by itself, and (2) it can provide output voltages nearly equal to its power supply voltages, resulting in maximum dynamic range. The output of the integrator is sampled by a 12-bit A/D converter at 20 Hz. The digital data stream is telemetered to ground and stored there. When the output of the integrator gets close to either the positive or negative limit, the microcontroller closes a switch that shorts out the integrating capacitor, resetting the integrator. The integrator uses a 0.1 µF capacitor; the ‘on’ resistance of the switch (DG304) is about 30 Ω. To be sure that the capacitor is fully discharged, the switch has to stay closed for five RC time constants or not less than 15 µs. There is also a built-in 1-µA current source that the microcontroller turns on for a few hundred milliseconds at power-up and again during the flight if a few hundred consecutive samples are nearly the same. The system diagram is shown in Fig. 4.

3. Observations

We flew the line current sensor into a thunderstorm over Langmuir Laboratory, in the Magdalena Mountains of central New Mexico. The balloon was released at 1940 UTC on 3 Aug 1996. The integrated current is shown as a time series (with altitude noted) in
From about 4 km to about 5.7 km, the line current was 0.02 nA, while the electric field initially was less than 10 kV/m, climbed to 17 kV/m and then dropped back to 5 kV/m. Then, at about 5.7 km altitude, we measured current of 0.12 nA, where the field exceeded 10 kV/m for the second time. At 6.2 km the current increased to 0.85 nA when the field had risen to about 25 kV/m. Above 6.3 km, telemetry from the field meter was too weak to receive (because of a hardware problem at the ground), ending the electric field data for this flight. The current then briefly went to −2.1 nA, then rose to as high as +2 nA, then decreased to near zero. During this time, the balloon rose to about 6.9 km and burst; then the instrument train came down on its parachute. During its descent, the instruments likely fell into a higher field region of storm, because for about 2 min during the descent, we measured currents around 50–70 nA. Since the line current

![Electric field vs. altitude](image1)

![Expanded view of high current period](image2)

Fig. 5. Shown here is a time series of integrated current; the slope of this trace is the line current. The horizontal axis has been translated to altitude. The upper trace shows the entire flight (about 1500 s), with balloon burst occurring at 6.9 km. The two spikes that occurred prior to 4.0 km were self-calibration pulses of 1 μA. The lower trace is an expanded view of the high current period (about 100 s), encountered upon descent between 5 and 4 km. The maximum current during this time was about 70 nA. The rapid transitions to near zero are caused by the integrator reset switch. The smaller ‘jumps’ are either current bursts or telemetry dropouts.
data were very noisy at this time, it is difficult to determine the current exactly; it may have been as low as 20 nA or as high as 100 nA.

4. Discussion

Although Jonsson (1990) measured current in nylon monofilament lines, his experimental setup was quite different from balloon rigging lines as flown. He set up a power supply and connected various types of continuously wetted lines across the power supply terminals. He found that with a potential gradient of 2 kV/m (500 V applied across a 0.25-m-long piece of rigging line), he could get currents to flow in wetted, Zepel-treated monofilament of up to 1 nA. With a field of 10 kV/m (five times as large) we measured a current of 0.02 nA (fifty times smaller). During a balloon flight, the rigging line is an isolated piece of ‘conductor’ through which no current flows unless a ‘circuit’ is made. This happens only when the upper and lower parts of the instrument train emit corona ions. We speculate that this is why our measurements are so different —Jonsson (1990) attached his lines to his power supply with wires; our line is connected to the thunderstorm’s ‘power supply’ via corona. The impedance at these corona sources is in series with the rigging line, and helps to reduce the total current.

Using the new instrument described herein, we measured rigging-line currents inside a thunderstorm that ranged from 0.02 nA up to possibly as high as 100 nA. Admittedly, this one balloon flight was not optimal, due to the failure of the field meter telemetry. But it was enough to show: (1) that the line-current instrument works, (2) that currents do flow along the rigging lines, and (3) what order of magnitude current we might expect.
expect. Now the question remains: is this current significant? Or, how much current must flow in the rigging line to have an effect on our \( E \) and particle-charge measurements?

There are two effects that the rigging line might have on the ambient electric field at the location of the EFM. First is the emission of corona ions (of opposite charge) from the ends of the line. This effect will serve to reduce the field at the EFM. Second, since the line is somewhat conductive, and since the EFM is directly below the end of this long thin conductor, it will cause an enhancement of the field at the EFM. These two effects will be treated separately.

4.1. Emission of corona ions

A reasonable place for corona ions to be emitted is at the swivel, about 1 m above the EFM (recall Fig. 1). For the following calculations we will use a geometry that is a vertical line, 9 m in length starting 1 m above the EFM; the coordinate system is shown in Fig. 7. Assume that the field is pointed vertically upwards or \( E = +E_z \); this means that positive ions will be emitted from the top of the line and negative ions from the bottom. Next, we make some simplifying assumptions which will be accounted for later. Each assumption will make the field alteration worse than reality, so the calculation will give a ‘worst-case’ value. First, we assume that the corona ions emitted off the ends of the rigging line will stay in a line, forming a line of charge. Second, we assume that the current has been flowing at a steady value ‘long enough’ that the line charge will be

![Diagram](image)

Fig. 7. Coordinate system for corona charge calculations. The electric field meter (EFM) is shown at the origin, and the rigging line stretches from 1 to 10 m. The lower integral limit is \(-1\) m.
constant 'to infinity.' Since the field contribution decreases as \(1/r^2\), 20–30 m away is nearly at 'infinity.' At the balloon's rise rate of 5 m/s, this distance is achieved in 4–6 s.

When corona ions are emitted, they travel on the order of 10 m in cloudy material before attaching to a hydrometeor (Brown et al., 1971). In rainshafts or other downdrafts, they travel even farther. The ion speed is a function of field strength, and ranges from a few to a few tens of meters per second. The exact calculation of electric field alteration would have to consider the appropriate, field-driven ion speeds in the appropriate directions, until the ions had moved 10 m. Then after the ion attaches to a hydrometeor, its speed goes to (nearly) zero. In order to simplify the calculation, we consider the two extremes: (1) the ions never attach to hydrometeors and (2) the ions instantly attach to hydrometeors. The real answer will be somewhere between these two extremes and will depend on the types and number densities of particles present.

The negative charge will be a line of charge extending from 1 m above the EFM to negative infinity. The 1 m of line charge above the EFM and the 1 m of charge below the EFM cancel by symmetry, leaving the charge from 1 m below the EFM to negative infinity. Written as an integral,

\[
E = \int_{-1}^{1} \frac{\lambda}{4\pi \varepsilon_0} \frac{dz}{z^2} = \frac{\lambda}{4\pi \varepsilon_0} \left[ \frac{1}{z} \right]_{-1}^{1} = \frac{\lambda}{4\pi \varepsilon_0}
\]

(1)

Line charge density, \(\lambda\), can be calculated by \(\lambda = I/v\), where \(v\) is the speed of ions driven by the electric field. This was was measured by Varney (1953); for our range of \(E\) and \(p\) (atmospheric pressure), the ion speed is \(v = 2 \times 10^{-4} \text{ m/s per V/m}\). So for a field strength of 10 kV/m, \(v = 2 \text{ m/s}\); for 100 kV/m, \(v = 20 \text{ m/s}\), relative to the balloon. From our measurements we found a steady current of about 0.2 nA in a field of 10 kV/m. These values give \(\lambda = -0.1 \text{ nC/m}\). The strongest fields we typically measure in thunderstorms is on the order of 100 kV/m. Note that if both measured values are increased by an order of magnitude, i.e., to 2 nA and 100 kV/m, \(\lambda\) does not change. So, for this amount of negative line charge density below the EFM, Eq. (1) gives \(-4.5 \text{ V/m}\).

Similarly, the second part can be calculated as follows

\[
E = \int_{1}^{10} \frac{\lambda}{4\pi \varepsilon_0} \frac{dz}{z^2} = \frac{\lambda}{4\pi \varepsilon_0} \left[ \frac{1}{z} \right]_{1}^{10} = \frac{\lambda}{40\pi \varepsilon_0}
\]

(2)

So for a positive line charge density above the top of the line of \(+5 \times 10^{-10} \text{ C/m}\), Eq. (2) gives about \(-0.5 \text{ V/m}\).

Now assume a worst case: we measured currents up to about 70 nA; what if the current flowing in the line was much bigger than that, say 1 \(\mu\)A? This would also require the assumption of a very large field value. In a very few cases, the balloon-borne EFM has measured a peak field as large as 150 kV/m. This field strength would result in an ion speed of 30 m/s, and a line charge density of \(\lambda \approx 33 \text{ nC/m}\). Using this value for \(\lambda\), Eq. (1) gives \(-300 \text{ V/m}\) and Eq. (2) gives \(-30 \text{ V/m}\), giving us a total electric field contribution of \(-330 \text{ V/m}\), or about 0.22% of 150 kV/m.
Up to now, we have assumed that the corona ions remain unattached, free ions for the duration of their field contribution. Now, we take the opposite stance and assume that they immediately attach to cloud particles and immobilize. In this case, the negative charge still extends from the bottom of the line to negative infinity, but the positive charge now extends from the top of the line to negative infinity. So the negative charge is completely cancelled, and the only positive charge left uncanceled is along the rigging line—from 1 m above the EFM to 10 m above. This integral is

\[ E = \int_{+1}^{+10} \frac{\lambda}{4\pi\varepsilon_0} \frac{d\zeta}{z^2} = \frac{\lambda}{4\pi\varepsilon_0} \left[ \frac{-1}{z} \right]_{+1}^{+10} = \frac{-9\lambda}{40\pi\varepsilon_0} \] (3)

This time, the field meter is moving towards the line charge at the rise rate of the balloon, about 5 m/s. For a large current of 1 \( \mu \)A (and field of 150 kV/m), this gives us a line charge density of 200 nC/m. Evaluating Eq. (3) we get a contribution of \(-1.6\) kV/m or about 1% of 150 kV/m.

Lastly, we account for our simplifying assumptions. We assumed that the charge coming from the ends of the rigging line remains in a line; actually, the charge spreads apart due to mutual repulsion and forms a plume which is conical for a distance, then straight along the field lines as a cylinder. This means that the charge will spread out, placing it farther from the EFM, reducing its field contribution. Another way of thinking of this: originally, we invoked symmetry to cancel the line charge 1 m above and 1 m below the EFM, but because the charge is not in a line, symmetry is broken; in the meter above the EFM the charge is more intense than stated, so it will cancel more than 1 m of charge below the EFM. This means the upper limit of integration in Eq. (1) might really be \(-2\), reducing the field contribution from Eq. (1) by a factor of 2. We also assumed that the currents flow for a ‘long’ time, say 10 s, at a steady value. The data show that for most of the flight the current was steady or slowly varying.

4.2. Field enhancement due to the rigging line

Like most real world electrostatics problems, this problem has difficult geometry and imperfect materials. We will approximate the line as a long, thin ellipsoid-shaped conductor. Smythe (1950) has solved the problem of the field outside a conductor shaped as an ellipsoid. Moore (1983) applied that calculation to the problem of lightning rods. The following calculation benefits from both of these examples.

Smythe worked this problem in a mixture of cartesian and confocal ellipsoidal coordinates. The confocal ellipsoidal coordinates, \( \eta \) and \( \xi \), represent a family of ellipses and hyperbolas, respectively. Since we are interested in the field directly above or below the tip, our point of interest falls on a line of constant \( \xi = 1 \).

We begin by defining the ellipsoid of the conductor itself. The monofilament line is 2 mm in diameter and about 10 m long. A loop is tied in the ends of the line for attaching instruments. This loop is stretched taut in flight, so the bottom end of the loop has a width of about 10 mm. This gives \( b = 5 \) mm and \( c = 5 \) m, where \( b \) and \( c \) are the ellipse’s semiminor and semimajor axes, respectively. The radius of curvature is then given by \( a = b^2/c = 5 \) \( \mu \)m. We now define the ellipse that is coincident with the
surface of our ‘conductor,’ \( \eta_0 = 1/\sqrt{1-a/c} \). Another needed parameter is the height of the focus of this ellipse, which is given by \( h_1 = c\sqrt{1-a/c} \).

We wish to calculate the field at a point 1 m from the tip of the ellipsoid. In this coordinate system, the middle of the ellipse is at \( z = 0 \), so the tip is at \( z = 5 \) m, and the point of interest is at \( z = 6 \) m. Next, because the field point is directly in line with the tip, the \( \eta \) coordinate is simplified to a function of \( z \) and \( h_1 \),

\[
\eta = \frac{\sqrt{z^2 + h_1^2 + \left((z^2 + h_1^2)^2 - 4h_1^2z^2\right)}}{h_1\sqrt{2}}
\]

and the field enhancement is given by

\[
\frac{E_q}{E_0} = 1 - \frac{\coth^{-1}\eta - 1}{\eta} + \frac{1}{\eta(\eta^2 - 1)} \left( \coth^{-1}\eta_0 - \frac{1}{\eta_0} \right)
\]

where

\[
\coth^{-1}\eta = \frac{1}{2} \ln \left( \frac{\eta + 1}{\eta - 1} \right)
\]

These chosen values give a field enhancement of about 25% at a distance of 1 m from the tip. If we assume that our wetted monofilament line is at least two orders of magnitude less effective in field enhancement than a perfect conductor, then the enhancement is 1% or less. Since Jonsson (1990) measured the resistivity of wetted, Zepel-coated monofilament line and found it ranged from \( 10^9 \) to \( 10^{12} \) \( \Omega/m \), this seems like a safe assumption.

4.3. Effect of the rigging line on particle charge measurements

Jonsson (1990) also claimed that the current flowing along rigging lines might be affecting charged particle measurements. For this calculation, consider 1-mm diameter precipitation particles and 10-\( \mu \)m diameter cloud particles. It is very unlikely that a precipitation particle will collect an emitted corona ion, since in a given volume there are so many more cloud particles (Pruppacher and Klett, 1978). So we will assume that the corona ions emitted by the line are captured by cloud particles. The \( q-d \) sensor (Bateman et al., 1994), which measures the charge of particles falling through it, is configured so that it is about 2 m horizontally from the nylon monofilament line. We will assume that the emitted corona ions evenly distribute in a 2-m radius circle, or an area of \( A = 12.6 \) m\(^2\), before attaching to cloud particles.

This calculation is similar to the one above where ions attached immediately to cloud particles. For reasons mentioned above, the only place where the emitted charge has not yet been canceled is along the line, or a length of about 10 m. A balloon rise rate of \( v = 5 \) m/s and a large current of \( I = 1 \) \( \mu \)A gives a volume charge density of
\[ \rho = \frac{I}{vA} = 16 \text{ nC/m}^3. \] A 1-mm raindrop falling through this 10-m-long cylinder will sweep out a volume of 7.85 \times 10^{-6} \text{ m}^3. If it collects every cloud particle in that volume (worst-case assumption), it will gain a charge \[ q = \rho V = 0.12 \text{ pC}. \] Note that the detection limit of the present \( q-d \) instrument is about 1–2 pC.

This calculation is a worst case. Note that typical values for \( |\rho_{\text{total}}| \) in small, isolated thunderstorms are 0.1–2.0 nC/m\(^3\) (Marshall and Rust, 1991; Marshall et al., 1995). Also, the emitted ions likely travel more than 2 m horizontally (Brown et al., 1971) before they attach to cloud particles, putting them beyond the \( q-d \) sensor.

Another problem that Jonsson 1990 mentioned was the emission of charged hydrometeors from the line. As we have mentioned previously (Bateman et al., 1994), the chance of ejecting a droplet at the exact azimuth and elevation angle to make a clean pass through the \( q-d \) sensor seems extremely remote, especially considering the balloon’s 5 m/s upward velocity relative to the air.

5. Concluding remarks

We have measured current flowing along balloon rigging lines inside a thunderstorm. Extrapolating from these data, we have calculated upper limits for reduction in \( E \) due to the emission of corona ions from the ends of the nylon monofilament rigging line. The reductions range from 0.22% to 1%. Also calculated was the enhancement of \( E \) due to measuring the field 1 m off the end of and directly in line with a long, thin, ellipsoidal conductor—around 25%. At worst, wetted Zepel-treated nylon monofilament line might result in an enhancement of 1%. Both ion emission and field enhancement are very small effects. We have also calculated the effect that corona from the rigging line might have on charged particle measurements. At worst, it might alter the charge on a particle by 0.1 pC, but is likely much less than this.

Jonsson and Vonnegut (Jonsson, 1990; Jonsson and Vonnegut, 1995) argue that current flowing in the rigging line might be significantly altering our electrical measurements. The measurements and calculations reported herein show that we are justified in stating that these effects are negligible, even with currents of up to 1 \( \mu \text{A} \) flowing in the rigging line. These measurements and calculations also support the conclusions of Marshall and Marsh (1995) that current flow in balloon rigging lines have a negligible effect on electric field and precipitation particle charge measurements inside thunderstorms.

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