GEOPHYSICAL RESEARCH LETTERS, VOL. 8, NO. 7, PAGES 783-786, JULY 1981

DIRECT MEASUREMENT OF LOWER ATMOSPHERIC VERTICAL POTENTIAL DIFFERENCES

R. H. Holzworth, M. H. Dazey, and E. R. Schnauss

Space Sciences Laboratory, The Aerospace Corporation, Los Angeles, CA 90009

O. Youngbluth

NASA Langley Research Center, Hampton, Va. 23665

Abstract. A high impedance system has been developed to make direct measurements of the atmospheric potential difference up to several thousand feet. A tethered balloon flown from Wallops Island, Virginia was used to loft a high voltage, insulated wire and a conducting collector in a test flight to 550 meters for two days of experiments in October 1980. The balloon was equipped with a payload to measure exact altitude, wind speed and direction, and other meteorological parameters. Electric potentials of 170,000 volts at 550 meters were measured. The collected currents which could be drawn through the wire by grounding the lower end were in the 10 microamp range indicating a system impedance of about 10^{10} ohms. This paper will describe the apparatus and details of these measurements.

Introduction

The fair weather atmospheric electric field is believed to be dominated by the return current from the action of world wide thunderstorms in a global circuit (Wilson, 1906; Israel, 1973; Holzworth, 1981). The atmospheric fair weather electric return current thus derived is about 1 to 2 picoamps/m^2, and is supported by atmospheric electric fields of the order of a few hundred volts/ meter at sea level where the conductivity is about 10^{-14} Siemens/ meter. Thus a point measurement of the atmospheric electric field in calm, clean air can be related to the global thunderstorm circuit. However, local winds tend to convect electric charges more easily than they can be conducted by these potentials and thus the electric currents are driven as much or more by convection than by the potential gradient. This effect complicates the interpretation of any single electric field point measurement in terms of global electrical phenomena. Due to this difficulty attempts have been made to measure a large portion of the ground-ionospheric potential difference. Two methods have been used: airplane or balloon soundings of electric field measurements which are integrated in altitude (cf. Muhleisen and Fischer, 1958; Markson and Vonnegut, 1971); or use of a tethered balloon to physically bridge a fraction of the total potential (Vonnegut et al., 1973).

These two methods have both yielded information about atmospheric electrical phenomena; however, both suffer from certain technical difficulties. The electric current and field soundings technique has been used to indicate that potential differences up to several hundred kilovolts is the average to be expected between the ground and the ionosphere (cf. Muhleisen and Fischer, 1958). However, time resolution of the atmospheric potential is difficult to obtain with this airborne sounding method on time scales faster than days without great expense (i.e., multiple flights). Furthermore, the lowest altitude measurements in these soundings (below the convection boundary) are the most variable and thus introduce an uncertainty in precisely the region of largest electric fields. Therefore, it would be more convenient to use a tethered balloon (as in the Vonnegut et al. (1973) method) to lift an antenna to hundreds of meters for essentially continuous measurements at high time resolution. In Vonnegut's tethered balloon system, a large conducting sphere is raised with the balloon and attached through a long steel wire to a high voltage power supply on the ground. A field meter up near the sphere is used to determine when the power supply voltage is the same as the atmospheric potential difference. Unfortunately, this means that a large portion of the steel cable is in corona discharge which results in space charge being emitted which can disturb the overall electric field measurements.

A new tethered balloon system has been developed and flown which eliminates the corona problems and the need for a telemetry system and the large current, high voltage power supply. This paper will describe this apparatus and the measurements made with it during two days of balloon flights in October 1980.

High Voltage Measurement Apparatus

Figure 1 presents a schematic view of the instrumentation used in this experiment. A tethered balloon (not shown) and its independent Kevlar ® tether are used as a "sky hook" for the totally separate high voltage wire arrangement depicted in Figure 1. The system is designed to have a collector consisting of a conductor of small radius and sharp points at the upper end along with a conductor of large radius at the bottom connected by an insulated wire. Thus the top end will collect current until its voltage approximates the ambient voltage. In other words, if the top end, with its sharp points, becomes a few kilovolts different from its surrounding air a corona current will flow to equalize the potential. The large radius corona ball at the lower end is designed to be corona free up to about 400 kilovolts. Since the system is insulated from the ground by teflon legs, there is net zero current in the wire in the steady state. Thus, corona current may briefly flow at the upper end but rapidly decreases to zero. Even at voltage differences below the corona

Paper number 1L0721.
0094-8276/81/001L-0721$01.00

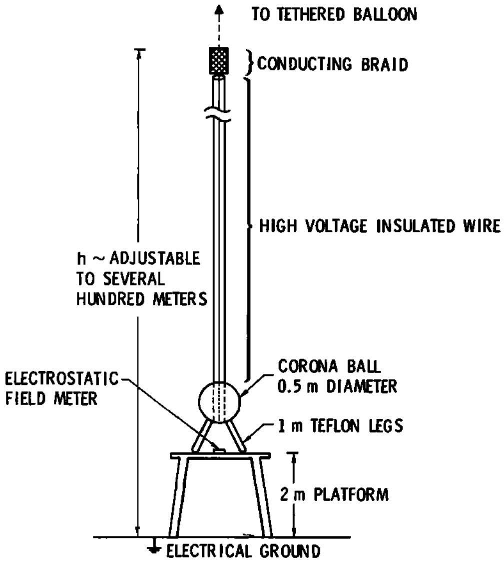

Fig. 1. Schematic of high voltage/high impedance system for tethered balloon experiment.

value for the upper collector, currents will flow due to the ambient conductivity in the presence of any electric fields near the sharp points. This will continue until the corona ball, high voltage wire and upper collector are at the same voltage as the air at the upper end of the wire. The measured time constant for this voltage equalization is a few tens of seconds as will be shown below. At 150 kilovolts the high voltage wire itself has a measured impedance which is two orders pf magnitude higher than the atmospheric source impedance. The actual voltage measurement is made with an electrostatic field probe (i.e. a field mill) placed about one meter from the corona ball. The impedance of the corona ball on its teflon legs was measured to be greater than 10^{14} ohms by observing the resistance-capacitance (RC) decay from 100 kilovolts. The entire system is calibrated in situ with a high voltage power supply. The required current from the power supply is nominally 1 microamp instead of the 1 to 5 milliamp supply required by the method of Vonnegut et al. (1973). Regular calibrations can be conducted to prevent local moisture variations and charge migration from affecting the field mill readings. The corona ball and tripod along with all associated electronics were mounted on the back of a truck so they could be positioned directly under the balloon. An electrical ground was established with a copper grounding rod and the truck body was grounded. This point will be discussed later.

Laboratory measurements of the wire leakage currents were conducted with 150 meters of the wire charged to 150 kV and inserted in a grounded bucket of salt water to maintain good electrical contact along the entire wire. A leakage current of 40 nano amps was measured which scales up to 160 nano amps for the entire wire. This amounts to a total wire impedance of 10^{12} ohms. For the reader interested in repeating this experiment the following engineering details are provided. The high voltage wire is Belden #8866 18-gauge television hookup which has a mass of about 30 Kg/kilometer with a hanging length at which it will break of about a kilometer and a total resistance of 18 Ω. The corona ball was made out of two 21-cm radius stainless steel hemispheres with a 3-cm radius hole at the top. The unused portion of the high voltage wire remained on a metal spool placed completely inside the corona ball. The end of the wire was terminated in a lug electrically connected to the metal spool which makes good electrical contact with the inside of the corona ball. The upper end of the wire was clamped to a current collector consisting of 8 meters of one centimeter diameter metal braid which was frayed at the end thus exposing the individual wires of 35 gauge (~ 0.2 mm) tin plated copper. The braid was attached 25 meters below the balloon with nylon rope.

Observations

An example of the atmospheric potential obtained by the method described above is presented in Figure 2. The data for this figure were obtained on October 23 during a four hour tethered balloon flight near local noon. The "error bars" in Figure 2 show the typical altitude fluctuations of the balloon and resulting voltage variations. Also shown in Figure 2 are the electric current values which were drawn from the antenna when the corona ball was grounded through a 10^9 ohm resistor. These current readings are very close to the short circuit electric current values since the system impedance is an order of magnitude higher than this resistor, as discussed below. The 10^9 Ω resistor is used to limit the discharge current to avoid high surge currents.

The impedance to the air of the system was measured by briefly grounding the ball and then letting it charge up. A sample of this measurement is shown in Figure 3. First the ball is grounded through a 10^9 Ω resistor and the voltage decays to about 20 kilovolts. Then a direct short to ground is made. The total system capacitance is found from the discharge time constant

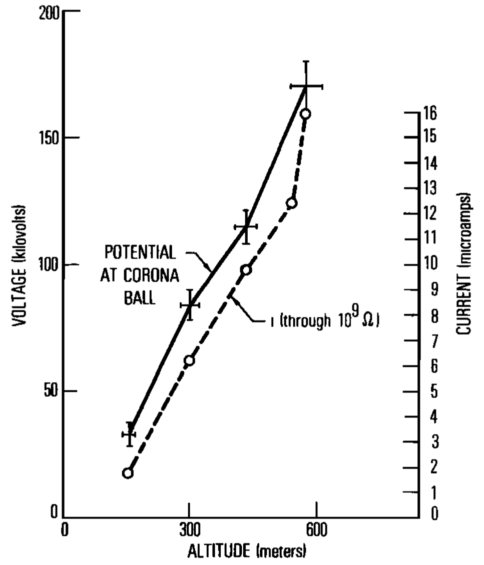

Fig. 2. Voltage and current values with altitude.

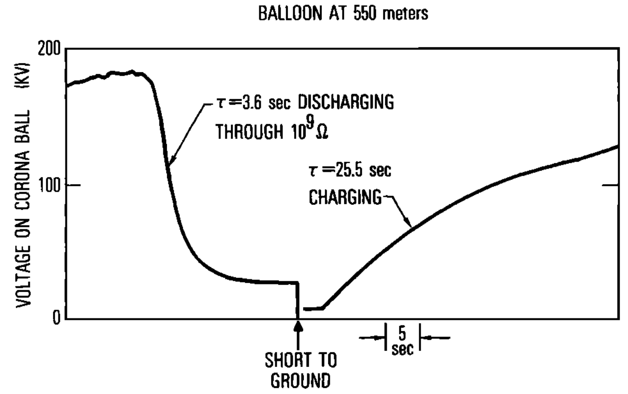

Fig. 3. Sample discharge and charge current with balloon at 1800 feet.

through the 10^9 Ω resistor (cf. Figure 3) of 3.6 seconds corresponding to 3600 pf. The time constant of the charging curve is about 25.5 seconds in this case. Thus the impedance of the system determined from the charging characteristics is 0.7 x 10^{10} Ω. The measured capacitance of 3600 pf is ~ 2.0 pf/foot of altitude which agrees well with the calculated capacitance of a long wire (Jasik, 1961). The wire required was about 25 percent longer than the altitude due to the catenary shape caused by the wind. Table 1 shows several charging and discharging measurements at different altitudes.

The measurements shown in Table 1 were obtained from a variety of altitudes under various atmospheric conditions on October 23, 1980. The balloon was raised in steps of roughly 150 meters beginning at 11 a.m. local time. The weather was somewhat windy with gusts of up to 10 m/s at times and a very high cirrus cloud cover was visible beginning about noon and getting progressively more dense. However, even at completion of data collection the cloud cover was so slight that clearly defined shadows were visible. While the measurements in Table 1 were taken under a variety of different conditions, there is good consistency shown in the last column. The average impedance of this system, independent of altitude, is 0.78 ± 0.03 x 10^{10} Ω. Ten separate charging curves are summarized at four altitudes in this table.

Table 1. System Parameters

h (meters)	Discharge thru 10^9Ω (sec)	System C (pf)	Charge (sec)	R ($\times 10^9$Ω)
150	1.45±.36	1450	12.0±1.0	8.3±0.7
300	1.99*	1990	15.2±4.4	7.6±2.2
430	2.78±.09	2780	21.7±0.0	7.8±0.0
550	3.89±.39	3890	29.5±5.4	7.6±1.4

*Only one sample available.

The variations in the measured potential shown by the "error bars" in Figure 2 and seen early in the voltage-time plot of Figure 3 are primarily due to altitude variations of the balloon. In Figure 4 the bottom three traces depict the altitude of the balloon along with the wind speed and direction for five minutes of data. As the balloon changes altitude in response to changing wind velocity as well as thermal and pressure balance considerations, the measured voltage also changes. Figure 4 shows a gradual dip and increase of balloon altitude with one short altitude jump in the middle. The voltage tends to follow the broad altitude variation but because of the high system capacity does not track the short term altitude peak. Figure 4 shows a short, highly variable time sequence during which the system probably never quite charged up to the average values shown in Figure 2.

Discussion

The voltages shown in Figure 2 agree well with those reported by Vonnegut et al., (1973) up to the 150 meter level. Above that, Vonnegut et al. obtained voltages which were no longer nearly linear with altitude but asymptotically approached 95 kV at 900 meters. The data in Figure 2 are therefore suggestive that corona space charge may have affected the performance of Vonnegut's apparatus above the 150 meter or 40 kilovolt level. Clearly the two measurements were made at very different locations and times and should not be expected to agree. However the essential difference is that our measurement is linear to nearly 200 kilovolts whereas Vonnegut's departs from linearity above 40 kilovolts.

The voltage measurements reported here when divided by altitude are within the expected range of electric fields measured on the ground (cf. Olson, 1971). The data in Figure 2 represent an electric field of about 250 to 300 volts/meter. Since the atmospheric conductivity has a scale height of about 6 km, the linearity of the data shown in Figure 2 with altitude is not surprising since 550 meters is about 10% of one scale height.

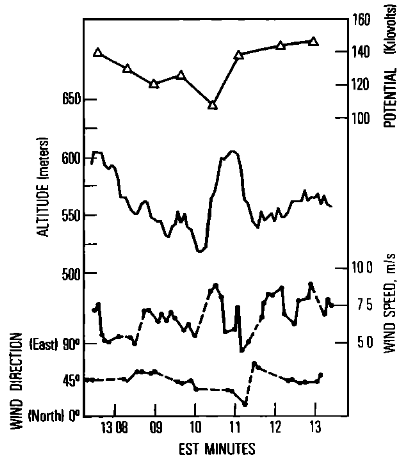

Fig. 4. Potential, altitude, wind speed and direction for a five-minute segment of data near 1310 (EST) October 23, 1980.

While the voltage measurements are within the expected range, the steady state short circuit current measurements are about five orders of magnitude larger than can be easily accounted for by the collection area alone. An ambient atmospheric electric current of 2×10^{-12} amps/m^2 would only result in about 365 picoamps for the collector if one assumes a collection area with a radius equal to the length of our collector. Thus, since 10 microamps are measured, a simple calculation suggests that all the fair weather current is collected from within an area of 5 square kilometers. This current is clearly related to corona discharge at the collector when the wire is grounded. We suggest that the steady state measurement of 10 microamps may not be simply due to corona current alone at the collector but that the total current results from an enhanced conductivity resulting in a larger effective collecting area. The cylindrical geometry of our conducting braid has a mathematically complicated potential distribution in space. This experimental paper is perhaps not the proper forum for a thorough theoretical analysis of the situation. However, by a simple analysis we can use the measured values of potential, impedance and current to calculate the ambient conductivity and current density as folows. The total current collected by the cross sectional area of a large sphere of radius α is $I_T = \pi\alpha^2 J = \pi\alpha^2 \sigma E$ where $J = \sigma E$ is the current density with σ = conductivity. The resistance to the air of a sphere of this radius is simply $R = (4\pi\sigma\alpha)^{-1}$ ohms (cf. p. 122, Burrows, 1978) and thus we can solve for α and σ in terms of measured quantities: $\alpha = RI_T/E$ and $\sigma = E/(4\pi I_T R^2)$. Therefore, using the measured values $E = 300$ v/m, $I_T = 10^{-5}$ amps and $R = 10^{10}\ \Omega$, we find $\alpha = 1332$ m $\sigma = 0.6 \times 10^{-14}$ s/m and thus $J = \sigma E = 1.8$ pa/m^2. The actual solution to our physical situation will be somewhat different than this simplistic analysis; for instance the radius α is larger than our tether length, so clearly the earth as a ground plane must be included in the calculation. We only wish to argue that the correct order of magnitude for the ambient conductivity and the ambient current density fall out of a simple analysis using our measurements. It should be emphasized that the current measurements involve corona at the collector while the voltage measurements were made at an equilibrium in which corona is absent.

Conclusions

From these measurements we conclude that a tethered balloon borne system can be used to measure large atmospheric potentials and therefore to monitor the variations with changing geophysical phenomena. A large fraction of the overall ground-ionospheric potential difference can be bridged by use of a tether only slightly longer than described herein. For instance, a 1500 meter high collector (by direct extrapolation of Figure 2 data) should be at a potential greater than 450 kV. We can conclude from the measured short circuit currents that such a long antenna, when grounded, couples to much larger portion of the atmosphere than was the case in earlier experiments which did not include corona enhancement to aid in current collection. Furthermore the atmospheric circuit impedance at 10^{10} ohms is much lower than earlier conductivity measurements might suggest.

One final note about safety for those wishing to duplicate these experiments. The wire has a capacitance of 3600 pf at 550 meters which is near 170 kilovolts and therefore represents a charge of 0.6 millicoulombs or a potential energy of 52 Joules! Therefore extreme care should be exercised in making measurements and grounds must be attached before handling the equipment.

Acknowledgments. This experiment was only possible because of the dedicated support by Mendel Silbert, Dave Boulter, and Bill Martin of NASA Wallops Flight Center and Dick Storey, Tom Owens, and Dan Poole of NASA-Langley Research Center. This research was supported at The Aerospace Corporation by NASA contract NAS6-3109.

References

Burrows, M. L., ELF Communications Antennas, Peter Peregrinus Ltd., Herts, England, pp. 245, 1978.

Holzworth, R. H., High latitude stratospheric electrical measurements in fair and foul weather, J. A. T. P. (in press) 1981.

Israel, H., Atmospheric Electricity, Jerusalem: Keter Press, 1973. (Available from U. S. Dept. of Commerce, NTTS doc. TT-67-51, 394/1 & 2, Springfield, VA 22151).

Jasik, Henry, Antenna Engineering Handbook, McGraw Hill, New York, First Edition, p 19-2, 1961.

Markson, R. and B. Vonnegut, Airborne potential gradient measurements of the temporal variation of the ionospheric potential, paper presented at IUGG, Moscow, August 1971.

Muhleisen, R. and H. J. Fischer, Radiosonden fur luftelectrische messungen, Arch. Tech. Mess., 274, 229-232, 1958.

Olson, D. E., PAGEOPH 84, 118, 1971.

Vonnegut, B., R. Markson and C. B. Moore, Direct measurement of vertical potential differences in the lower atmosphere, J. Geophys. Res., 4526, 1973.

Wilson, C. T. R., On the measurement of the earth-air current and on the origin of atmospheric electricity, Proc. Camb. Phil. Soc., 13, 363-382, 1906.

(Received December 22, 1980;
revised March 10, 1981;
accepted April 14, 1981.)