THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY SCHOLARS PROGRAM

DEPARTMENT OF ELECTRICAL
AND
COMPUTER ENGINEERING

MEASUREMENT OF MAXWELL CURRENTS USING AN ATMOSPHERIC ELECTROMETER

EDWARD J. NOVITSKY

SPRING SEMESTER 1992

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in electrical engineering
with honors in electrical engineering

Approved: [signature] Date: 28 April 92
Dr. C.R. Philbrick
Thesis Supervisor

[signature] Date: 28 April 1992
Dr. David Miller
Honors Advisor

[signature] Date: 4/28/92
Dr. Larry C. Burton
Department Head

TABLE OF CONTENTS

INDEX TO FIGURES

Introduction

The Geophysics Data Center (GDC) in the department of Electrical and Computer Engineering at The Pennsylvania State University is concerned with the collecting, storing and displaying of various information pertaining to the Earth's geophysical environment. The GDC has several instruments currently (spring 1992) built with more expected. This instrument, an atmospheric electrometer, is one of the instruments to be incorporated into the GDC.

The Electrometer measures the current in the atmosphere on a continuous basis. Current in the atmosphere is primarily caused by thunderstorms which can be thought of as the power supplies in the global circuit. The amount of current measured, however, is heavily influenced by atmospheric conditions, namely wind.

As a consequence of measuring atmospheric current, Earth's electric field strength can be inferred by calculation. However, an accurate reading of the electric field using an electrometer can only be made when stable atmospheric conditions are present. In order to reduce the effect of the environment, an electric field-mill should be employed to give an accurate readings of the electric field. The electric field-mill alternately exposes and conceals a metal plate to the atmosphere and measures the change of charge in a known time interval. For more information, see reference 6.

Another motivation for building an electrometer is cost. Commercially available electrometers sell for over $2000. The electrometer built in this paper costs about $400. The commercial electrometer does, of course have other options available.

at ground level is approximately 3 x 10^{-14} mhos/meter but this value can be greatly affected by weather conditions.

Electric Field

The charge distributions in the air give rise to an electric field. The fair-weather electric field is approximately 100 V/m but during intense storm activity, it can attain values upwards of 10 kV/m (2, p.462). As shown in Figure 2, the electric field falls of with altitude which is opposite electrical conductivity. Again, as with conductivity, the electric field, since it is a function of atmospheric charge arrangements, is greatly affected by weather conditions.

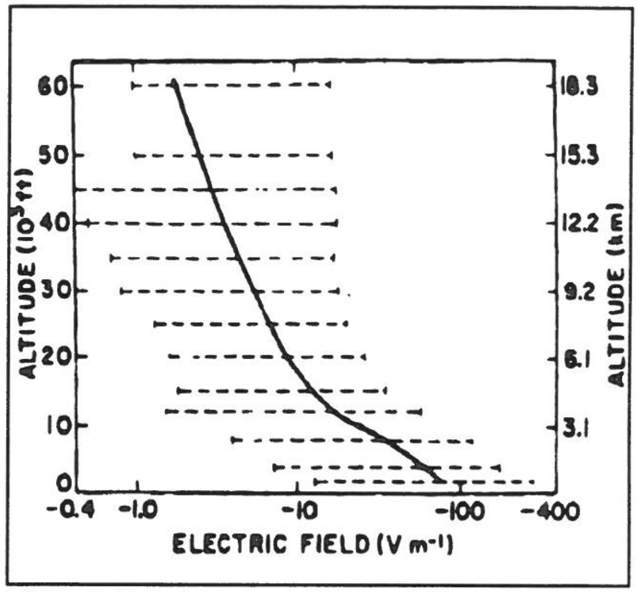


Figure 2 - Average Value and Maximum Variation of Electric Field as a Function of Altitude (1, p.20-4)

In order to sustain the fair-weather field, a process must exist which circulates charge, otherwise the electric field would dissipate. The regenerative mechanism is thunderstorm activity. On the average, there are about two thousand thunderstorms in progress at any given time (3, p.219 and 1, p.20-6). Figure 3 depicts the regenerative process. The charge moves from the thunderstorm, through the highly conductive upper atmosphere, down to the Earth and back to the thunderstorm thereby completing the loop. This loop is the global circuit and repeats continuously. The currents in the atmosphere are termed Maxwell currents.

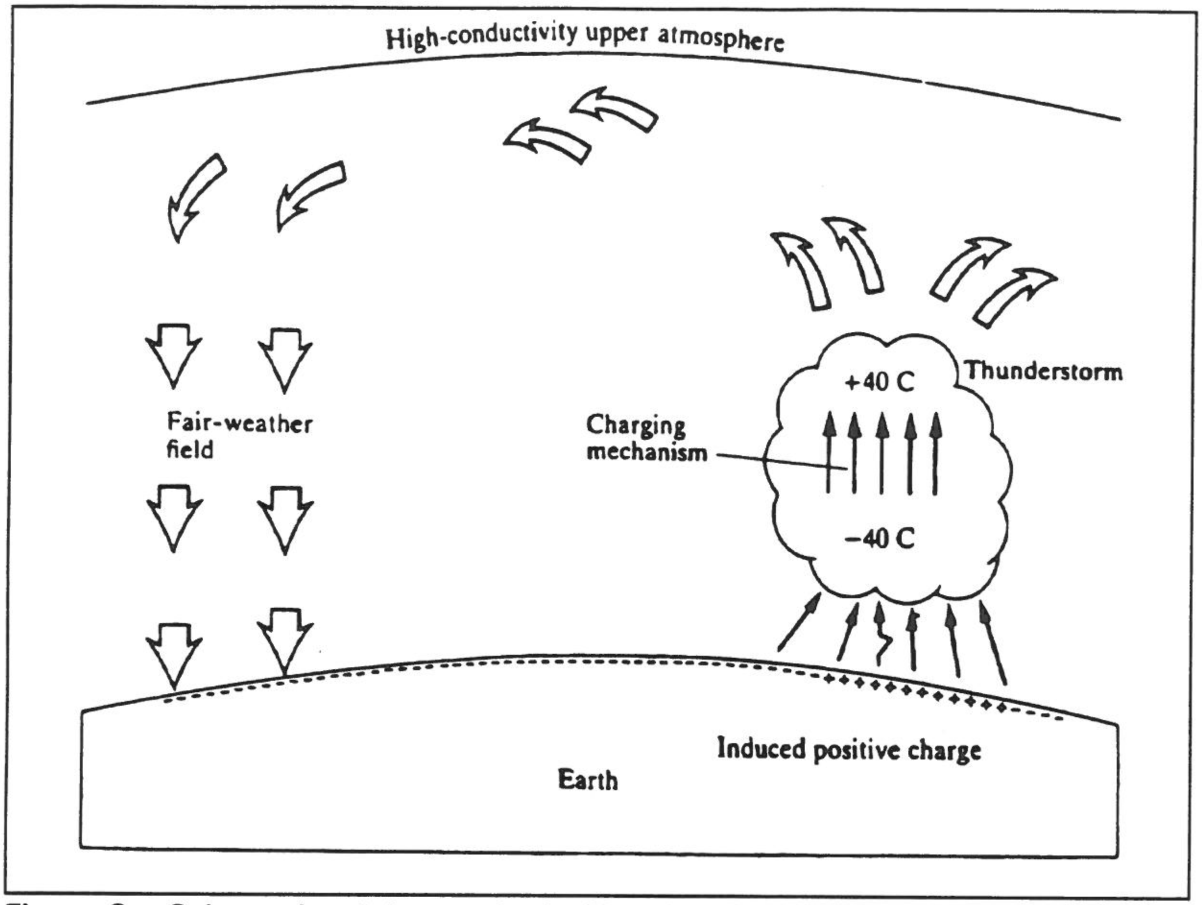


Figure 3 - Schematic of Atmospheric Charging From Thunderstorms, Which is Responsible for the Fair-Weather Electric Field Around the Earth (3, p.219)

Maxwell Currents

The current in the atmosphere is a collection of various currents and current processes. Collectively, these currents are termed Maxwell currents.

The principal component of Maxwell currents is the air-earth conduction current. This current flows due to the downward directed electric field and is given by

$$J_1 = \sigma E$$

If only air-earth conduction current is measured, then the electric field directly follows.

Secondary currents arise due to atmospheric conditions. In regions where a space charge exists, movement of air produces a transfer of charge defined as convection current and given by

$$J_2 = \rho v = -\frac{1}{4\pi}\frac{dE}{d'Z}V$$

where Z is altitude and V is the electric potential (1, p.20-5). Note that convection current is related to wind velocity v and is therefore affected by weather conditions.

As charge moves through the atmosphere, the electric field changes in magnitude and a potential gradient is produced. The changing of the electric field over time is called displacement current

$$J_D = \epsilon \frac{dE}{dt}$$

but this current is not appreciable unless the electric field varies rapidly over a small time interval.

These are not the only Maxwell currents. Additional currents may also arise from the solar wind impacting on the magnetosphere, from radioactive sources or from thermal agitation of a material.

Note that each of the currents discussed above have the electric field associated with their respective equations. If only air-earth conduction current was present, the electric field could be easily determined from the conduction current equation. However, the other currents may become substantial under favorable atmospheric conditions and these currents would represent an error in the calculation of the electric field. Therefore, measuring of atmospheric current may not be a desireable indicator of electric field strength.

Circuit Parameter Considerations

This section determines and discusses fundamental electric parameters associated with Earth's atmosphere and the basic schematic of the circuit used to measure atmospheric currents.

Electrical Property Calculations

Since the Earth's conductivity (approx. 10^{-4} mhos/meter) is large compared with the atmosphere's, the Earth can be considered an equipotential. The charge induced on the Earth's surface by a fair-weather field strength of 100 V/m is

$$q = \epsilon_o E \approx -(10^{-11})(10^{2}) = -10^{-9}\ C/m^2$$

and, over the Earth's surface, leads to a total charge of

$$Q_E = 4\pi R_E^2 q \approx -500{,}000\ C$$

where R_E is Earth's radius.

The conductivity of the atmosphere at ground level is approximately 3.0×10^{-14} mhos/meter and hence the current density from the same fair-weather electric field is,

$$J = \sigma E = (3 \times 10^{-14})(100) = 3 \times 10^{-12}\ A/m^2$$

Integrating this current density over the Earth's surface, the total downward current is,

$$I = J(4\pi R_E^2) \approx 1500\ A$$

So if, a 1m x 1m metal plate is placed parallel to the Earth's surface at a distance of

1m above the ground and the current (due to the fair-weather field) is measured, the expected value should be 3 pA. The magnitude of the current gives some indication to the strength of the electric field (3, pp. 218-219). The fair-weather field current density varies not only from atmospheric influences but also at different latitudes and longitudes.

Latitude Zone	Mean Current Density (pA/m^2)
Arctic	3.0
Northern temperate zone	2.1
Tropics	2.6
Southern temperate zone	2.4
Antarctic	3.0

Figure 4 - Zonal Distributions of Air-Earth Current Densities (1, p.20-2)

Figure 4 shows several current density variations for different regions on the Earth. The higher current densities at the poles are most likely the result of solar wind particles moving along Earth's magnetic field lines which terminate in these regions (1,p.20-5 - 7).

Circuit Model Schematic

A schematic representation of an atmospheric electrometer is shown in Figure 5. The basic components are a flat plate antenna and an RC network, which consists of a high-gain transducer amplifier. The electric field can be calculated by measuring the voltage on the plate (from measuring current through the R resistor). In the absence of any loading of the antenna (Figure 5a) the electric field near the antenna is E, and the potential difference between ground and antenna is V_g = Eh. The stray capacitance between antenna and cloud is C_c, between antenna and ground is C_g, where $C_g >> C_c$. The potential difference between cloud and ground is V. The cloud-to-ground potential difference is divided across the two capacitances C_c and C_g.

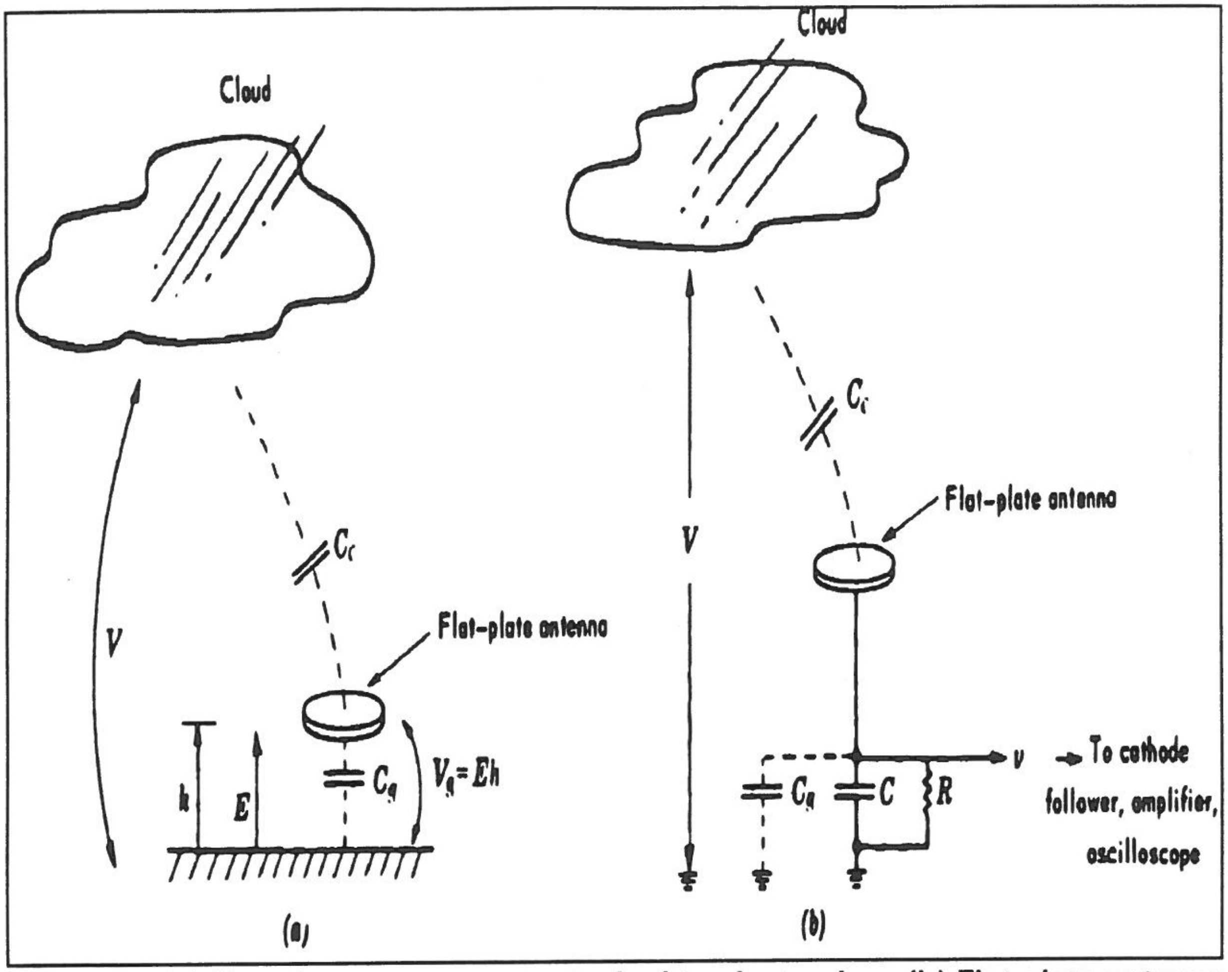


Figure 5 - (a) Flat-plate antenna not attached to electronics (b) Flat-plate antenna with associated electronics (4, p.64)

The potential difference across C_g is

$$V_g = V\frac{C_c}{C_g + C_c}$$

and, substituting for V_g,

$$V = Eh\frac{C_c + C_g}{C_c}$$

A potential v is measured which is less than V_g since the RC circuit loads the antenna. Assuming R is a very large impedance compared to C, we need to only consider the effects of C on the determination of v. Since C and C_g are in parallel, the voltage is given by

$$v = V\frac{C_c}{C_g + C_c + C}$$

and, by substituting for V,

$$v = Eh\frac{C_c + C_g}{C_g + C_c + C}$$

Since $C_g >> C_c$,

$$v \approx Eh\frac{C_g}{C_g + C}$$

Therefore, the measured voltage is proportional to the electric field E and the proportionality constants may be measured or calculated (4, pp.63-65).

Circuit Description

The complete circuit diagram is found on A-1. The following sections detail the circuit components and technical obstacles associated with implementation and design. The circuit is partitioned into the following elements: Electrometer-Grade operational amplifier, timing circuit, switch/amplifier, 3 1/2 digit DVM (PC board mount), and power supplies.

Electrometer-Grade Operational Amplifier

The OPA-128 Electrometer-Grade operational amplifier manufactured by Burr-Brown® is the heart of the electrometer. The OPA-128 is an **FET** amplifier with an exceedingly small input bias current. This is a very important feature which will be discussed shortly. Figure 6 presents the wiring configuration of the OPA-128 used in the circuit.

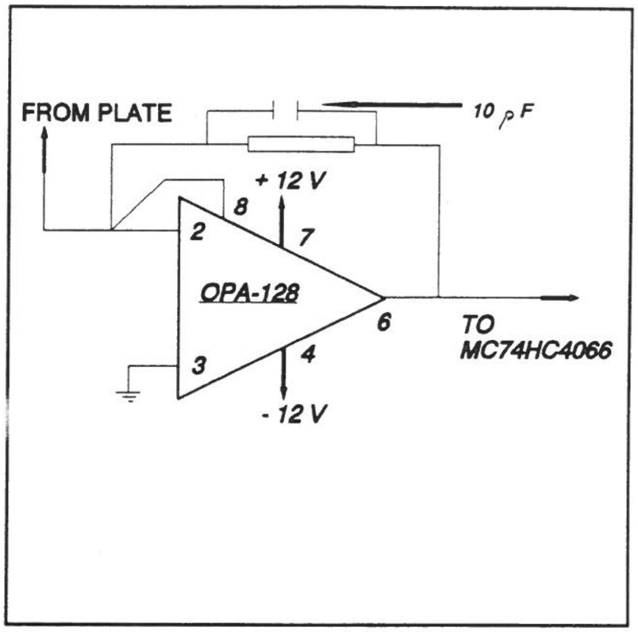


Figure 6 - OPA-128 Wiring Configuration

The 10^{10} Ω resistor in the feed-back loop is called a Victoreen and is composed of a high impedance material housed in a glass tube. Care should be taken in handling the Victoreen so as not to touch its glass housing (oils from the skin may perturb the resistor's value). From the Air-Earth conductivity equation, the input current, I, should range from 1 pA (corresponding to a fair-weather field of 100 V/m) to roughly 1 nA (corresponding to 10,000 V/m due to storm activity). Since the output voltage (at pin 6) is given by -IR, R must be great enough to provide a measurable voltage signal at the output. Thus, at 1 pA, the output voltage will be .01v and, at 1 nA, 10v and the amplifier will have a gain of -10^{10} (inverting configuration).

With such a high gain, any unwanted input signals with a current strength greater than or equal to 1 pA will contribute error to the measured signal. Thus, it is desirable to have an extremely low bias current which will not detract from the input signal so as to not affect the intended output voltage. The OPA-128 has a bias current of 75 fA (75×10^{-15}) compared to a 30 nA bias current of the standard 741 op-amp.

Since the feed-back resistance is enormous, the amplifier would tend to oscillate (due to input current fluctuations) without the capacitive stabilization provided by the 10 pF capacitor.

Timing Circuit

The timing circuit (Figure 7) is designed to sample current from the steel plate over a 5 second interval every 2.5 minutes. It would have been simpler to use an astable monovibrator circuit such as the 74123, but the timing demands would have made the capacitor and/or resistor values impractical.

The purpose of the timing circuit is to allow current to flow from the plate for only five seconds at a time. The motivation for using such time constraints is based on the following arguments. Consider a conducting sphere of radius a suspended and isolated in the atmosphere with a conductivity, σ. The electric field just outside the surface of the sphere is

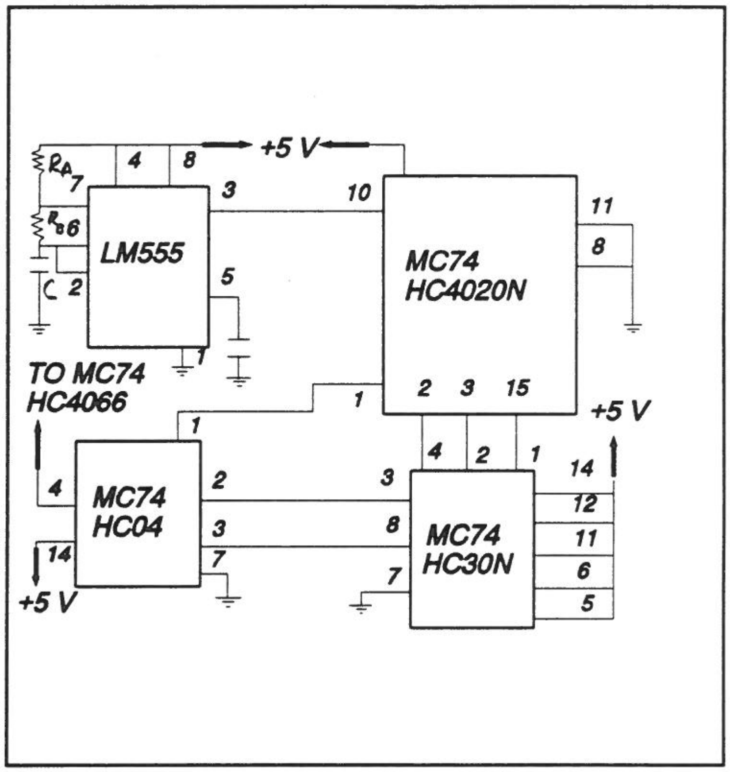


Figure 7 - Timing Circuit

$$E_r = \frac{Q}{4\pi\epsilon_o a^2}$$

and the resulting current density is $J_r = \sigma E_r$. The total current flowing away from the sphere is then

$$I = -\frac{dQ}{dt} = g E_r (4\pi a^2) = \frac{g}{\epsilon_o} Q$$

The differential equation for Q has the solution

$$Q(t) = Q(o)\, e^{-t/(\epsilon_o/g)}$$

The conductivity at sea level is $\sigma \approx 3 \times 10^{-14}\ (\Omega \cdot m)^{-1}$. Thus the decay time constant ϵ_o/σ of the charge is

$$\frac{\epsilon_o}{g} \approx \frac{9 \times 10^{-12}}{3 \times 10^{-14}} \approx 5 \text{ min}$$

Therefore, in the absence of a recharging mechanism, charge will leak from any conductor in the atmosphere in about 5 minutes. This applies to a conductor with any given geometry (3, p.218). So, if current is continuously drawn from the metal plate, current readings may be inaccurate due to loading of the plate by the circuit.

The LM555 is configured to be a current controlled oscillator through the variation of the 100k pot (R_A). The frequency of the oscillator is given by $f = 1.44/(R_A + 2R_B)C$. For fair-weather measurements, f = 100 Hz which makes R_A = 74 kΩ with R_B = 35 kΩ and C = .1 μF. As a storm approaches, more rapid time intervals may be desired and this is accomplished by lowering R_A.

The MC74HC4020N is a 14-stage binary ripple counter with 12 bits for a total of $2^{12} - 1 = 4095$ counts. In order to attain 5s pulses, the following bit scheme was used:

Count	Bit (MSB … LSB)
3328	1 1 0 1 0 0 0 0 0 0 0 0
3584	1 1 1 0 0 0 0 0 0 0 0 0

The difference between the two is 256 counts which, at 100 Hz, corresponds to a total time of 2.56s. The first, second and fourth most significant bits (MSB) are inputed into the MC74HC30 8-input NAND gate while the third MSB is put into the MC74HC04 Hex Inverter and then into the NAND gate. The output of the NAND gate is inverted and sent to a controlling gate of the MC74HC4066 switch.

Switch/Amplifier

The MC74HC4066 Quad Analog Switch (Figure 8) controls the signal from the OPA-128. When the output from pin 8 of the 8-input NAND gate goes low, the switch is turned on and passes the signal from the OPA-128 and stops the signal after 2.5s (at 100 Hz clocking frequency). The switch is a high-performance Silicon-Gate CMOS chip with low ON resistance and low OFF channel leakage current.

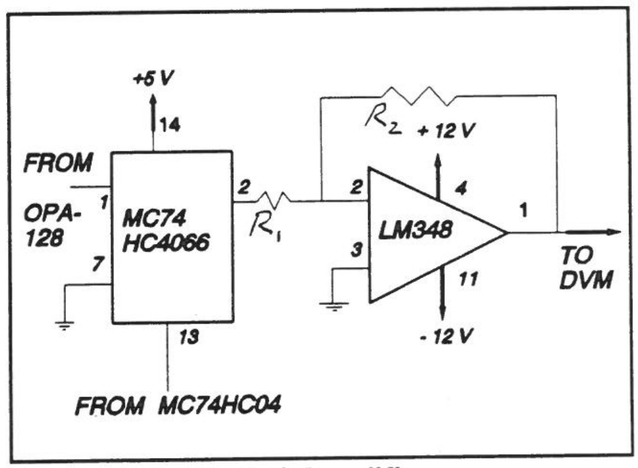


Figure 8 - Switch / Amplifier

The LM348 Quad operational amplifier is configured as an inverting amplifier with unity gain. The signal from the OPA-128 will be negative so the LM348 will make the signal positive. Also, since the LM348 is a Quad op-amp, it provides additional circuitry for up-grading while the remaining op-amps can be configured as comparators with hysteresis for determination of the decimal point placement on the digital panel meter (DVM).

Digital Panel Meter

The DMS-30PC-2-GL is a green 3 1/2 digit DVM (Figure 9). Its small size, low-power requirements, and portability make it ideal for PC board mounting. The signal from the LM348 is fed directly into the DVM without additional circuitry. The DVM has 2 digit accuracy and has a voltage range of +/- 20V. Since the voltage from the OPA-128 ranges from .01V to 10V, the DVM will be adequate for display purposes. Cost may be a factor in deciding to use the DMS-30PC ($49, 1992) however, the alternative is to design a digital voltage display using an A/D converter, LED drivers and latches, and LED displays all of which require additional power supplies and wiring. This may not be practical when and where space is a constraint.

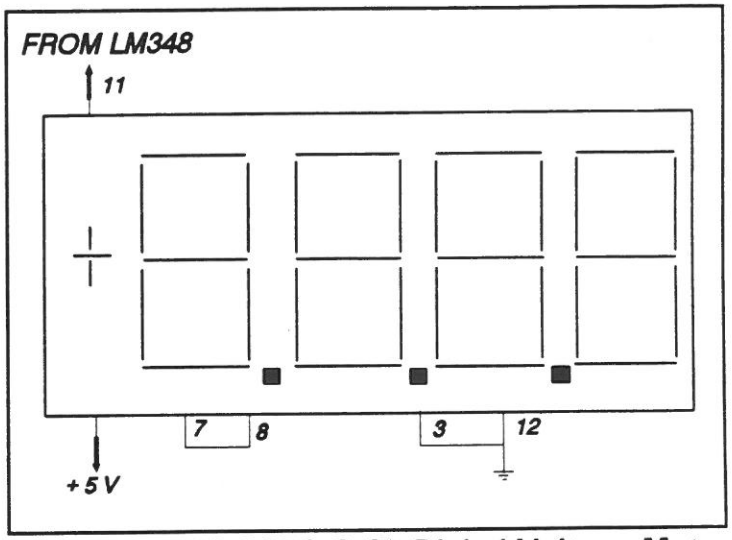


Figure 9 - DMS-30PC-2-GL Digital Voltage Meter

Power Supplies

The circuit has to be portable in order to take it into an open field where the wind flows more evenly and interference from buildings is kept to a minimum. Three, 1.5 V, 'D' batteries provide the circuit with power. 'D' batteries are expected to last approximately 80 hours while 'C' batteries are expected to last about 58 hours (5). The OPA-128 and LM348 require +/- 12V supplies while the rest of the circuitry (which are all low-power CMOS) require at least +5V. Thus, it was necessary to use three DC-DC converters. All three converters were chosen for their size and affordability:

CB3801	- 12V
CB3810	+ 6 V
CB3811	+12V

could be powered by a single 1.5v battery but it was decided that in order to prolong data time, an additional 1.5v battery would be connected in parallel with the first battery.

The three batteries are housed in 'D'battery holders and attached to the sides of an aluminum chassis box (See Figure 11). It should not be difficult to remove the batteries for replacement. Later, when a computer is available to record the data from the instrument, rechargeable batteries should be used.

Housing Assembly Considerations

Because of the sensitivity of the OPA-128 amplifier and the small current to be measured, it is vital to insure and maintain isolation between the amplifier and the rest of the circuit and between the amplifier and the atmosphere. For this reason, the entire electrometer circuitry is encased in an 8" x 6" x 3 1/2" aluminum chassis box (See p. A-3)

Each of the circuit components except the OPA-128 and DVM are mounted on a 6" x 3 1/2" bread board and the board is secured to the bottom of the box with electrical tape. The OPA-128 is secured, with the can side down, to the underside of the removeable aluminum chassis lid. A small layer of parafin helps to fasten the OPA-128 to the lid.

An aluminum plate serves as the antenna for the gathering of atmospheric current. The aluminum plate and electrometer instrumentation are attached together by Teflon threads. Teflon has an extraordinarily high resistivity which prevents current from traversing across its surface from the plate to the chassis box and interfering with the electrometer's readings. (The Teflon threads fit No. Rs-440A 4-40 x 1/4" L slotted round head zinc plated steel machine screws.) The output lead of the OPA-128 is fed into a hole in the chassis box and into pin 1 of the MC74HC4066. The input lead (pin 2) is soldered to the plate and pin 3 is connected to a battery ground.

There is a 12 inch wire lead running from the output of the OPA-128 to the analog switch along with 12 inch power supply leads leading to the +/- 12 V DC-DC converters. This is to provide enough length when the bottom of the box is removed for access to the power supplies or to change the frequency of the clock oscillator. When removing the bottom plate of the box, dislodge the wire from the bread board carefully.

The front display plate of the electrometer is on p. A-2. The switch has a test option in order to ensure that the DVM is functioning properly. **DO NOT LEAVE IN THE TEST MODE FOR MORE THAN 10 SECONDS.** When the switch is in the down position, the circuit begins operation and the green LED lights. When the red LED lights, the electrometer is taking readings. The switch, LEDs and DVM are sealed on the inside with wax to reduce the chance of signal corruption by stray atmospheric currents.

The Aluminum plate was chosen due to its low resistivity ($\rho = 1.7 \times 10^{-8}$ $\Omega \cdot m$) and cost (as compared to a plate of copper).

Calibration

With a 10^{10} Ω resistor in the feedback loop of the OPA-128, -.01 v should appear at the output due to an input current of 1 pA. This voltage corresponds to low range of the DVM. However, when is the world perfect? The Victoreen's resistance was calculated to be 8.961×10^9 Ω. The resistance has to be calculated since most multimeters are incapable of measuring such high resistances directly due to their finite input impedance. To measure high resistances, apply a known voltage and measure the current through the resistance under test. Calculate resistance using Ohm's Law.

With the measured value of the Victoreen resistor, a 1 pA input current will result in an output voltage of .008961 v. The DVM can not read this voltage so a compensating gain must be applied using the LM348. In order to get 1 v out of the LM348, R_1 = 10 kΩ and R_2 = 11.160 kΩ (ideally).

Measurements Using A Keithley Electrometer

Atmospheric current measurements were made using a Keithley Model 614 Electrometer as a way to calibrate the electrometer built in this paper. Graphs of these measurements are on pp. A-6 - A-7. Three different conductor configurations were employed: A 100 ft. piece of 24 gauge bare copper wire, 25 ft. piece of 18 gauge bare copper wire, .51344 m^2 aluminum plate. It is not the area of the collecting plate which is important, but rather it is the length. For example, a hollow sphere with radius d, collects the same amount of current as a wire of length d (L.C. Hale, The Pennsylvania State University).

When using the Model 614, be sure to keep the probe wire as still as possible so as not to invoke the triboelectric effect which can cause substantial error in the readings. The electrometer should have the ground and common pins on the back of the instrument connected. Also, when taking readings, do not move around the test conductor since the wind generated from movement also lead to considerable error.

Recommendations For Future Research

Ultimately, this project, along with several others which make up the Geophysical Data Center, will be connected to a central computer which will gather, correlate, and store data from the various projects. Due to the portability and necessary isolation of the atmospheric electrometer, a system needs to be devised to transfer the data collected to the computer. This can be done in many ways but I will list two.

The first is by radio wave transmission. Data would be transmitted by telemetry and received by an antenna connected to the computer.

The second is to have a tape recording system which would encode data on magnetic tape and then the tape can be taken back to the computer to be disseminated.

The batteries should be rechargeable. Also, external access to the potentiometer of the LM555 should be made.

Of particular interest in the geophysical environment is the electric field intensity. The atmospheric electrometer can infer electric field magnitude but not accurately since its measurements are highly dependent on atmospheric conditions. In order to measure the electric field, an electric field-mill should be employed. The field-mill does not measure current but rather current changes over a known period of time. The electric-field mill attempts to reduce the affect of the atmosphere on readings. The field-mill can be made to be sensitive enough to detect the electric-filed variations due to cloud-to-ground lightning strikes. For more information see reference 6.

Lastly, atmospheric current can vary enormously from femtoamps to tens of nanoamps. Preliminary data taken in State College, Pennsylvania shows a variation of roughly several picoamps to several nanoamps. This range uses the full display range of the DVM but if the atmospheric current moves outside of this range, the DVM will be unable to accurately display the current readings. For this reason, a logarithmic diode should be placed in the feedback loop of the OPA-128 in order to compress the current scale. This technique is extensively covered in reference 7.

Results

Simply put, the electrometer designed in this paper works...with external power supplies. I have determined that the problem with using internal power supplies (batteries) to be grounding and a combination of loading.

First, **POWER GROUND AND SIGNAL GROUND MUST REMAIN SEPARATE**. This was found when the CB3810 was producing 0 V at its output. For this reason, all negative leads of the battery supplies are connected directly to the ground pins of each converter.

Loading was found to be rampant. When powered with +5 V from the CB3810, the DVM produced loading. The loading encountered was not significant but it was a constant drain on the CB3810's power. I attempted to compensate by running the +5 V input lead of the DVM through a voltage follower configuration using the LM348. This resulted in a loading of the CB3811 and so was discontinued. The DVM needs **55 mA** at **+ 5 V**.

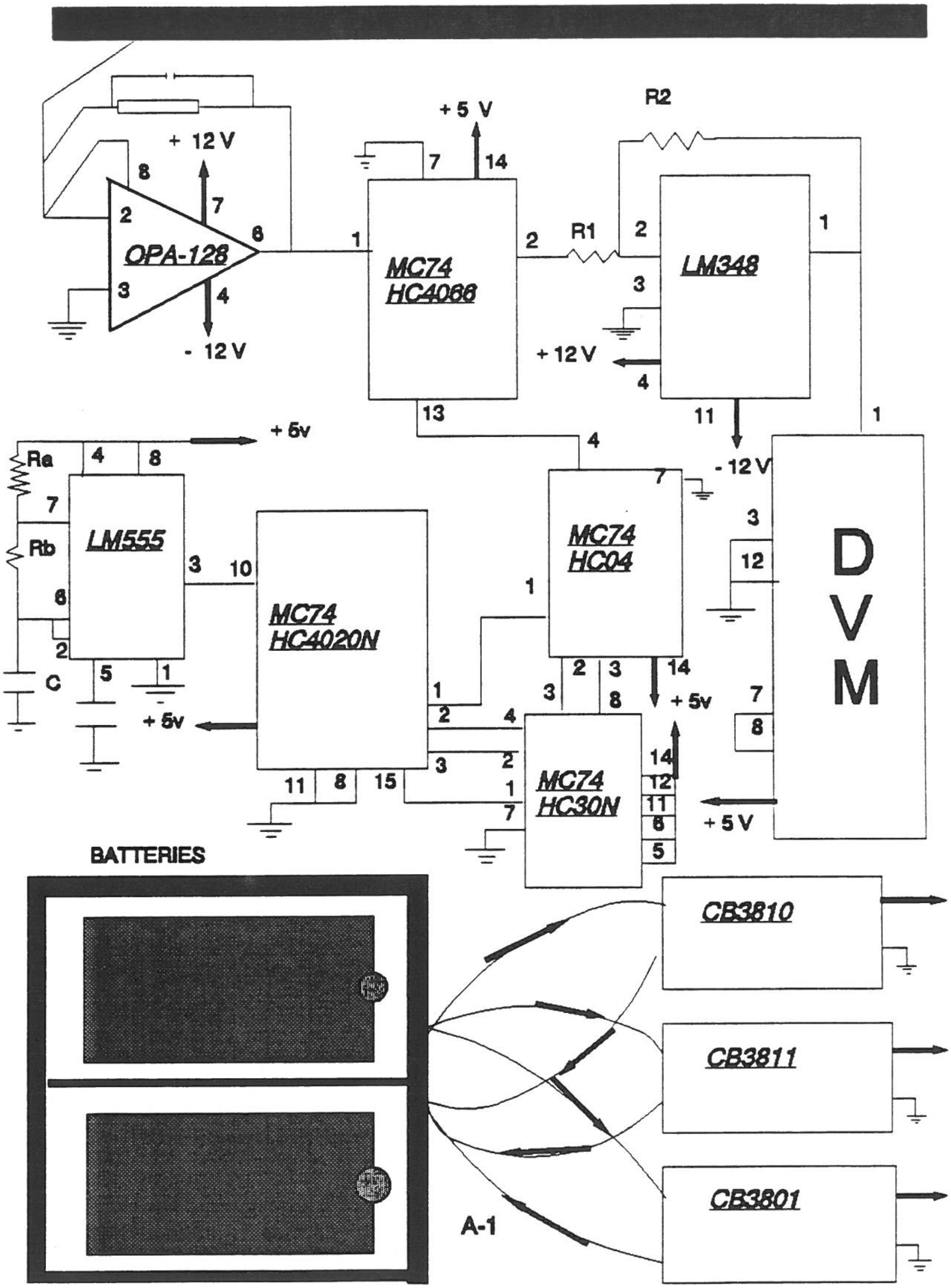
Loading of the -12 V supply occurred when the power lead was connected to the OPA-128. Another voltage follower configuration was initiated and subsequently failed. Loading, for some unknown reason, did not occur with the +12 V converter.

The loading problems lead me to believe that the battery supplies are not sufficient to power the circuitry. Additional power must be acquired but it can not take up much space in the aluminum housing. Another bank of batteries are required. I would suggest using several batteries to power the DVM and/or the OPA-128 alone.

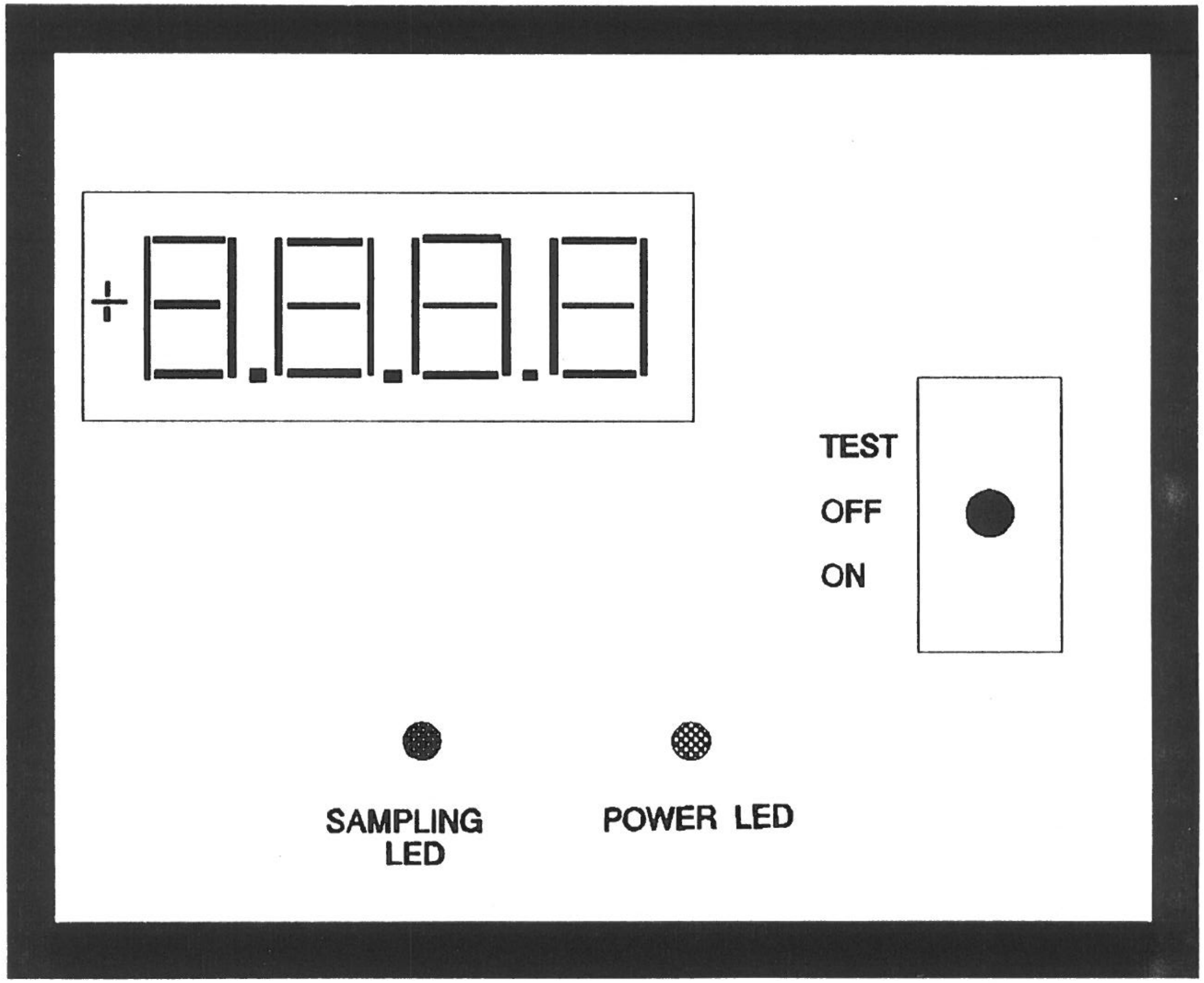
Upon graduation, I am taking a job where I will be working on satellite instrumentation. I hope to learn how power is supplied to the satellite's various components. This thesis, with its application to earth and space sciences, was an excellent stepping stone into the real world. I will be looking for answers to the questions I have brought up and so I will be ready when the answers present themselves.

APPENDIX

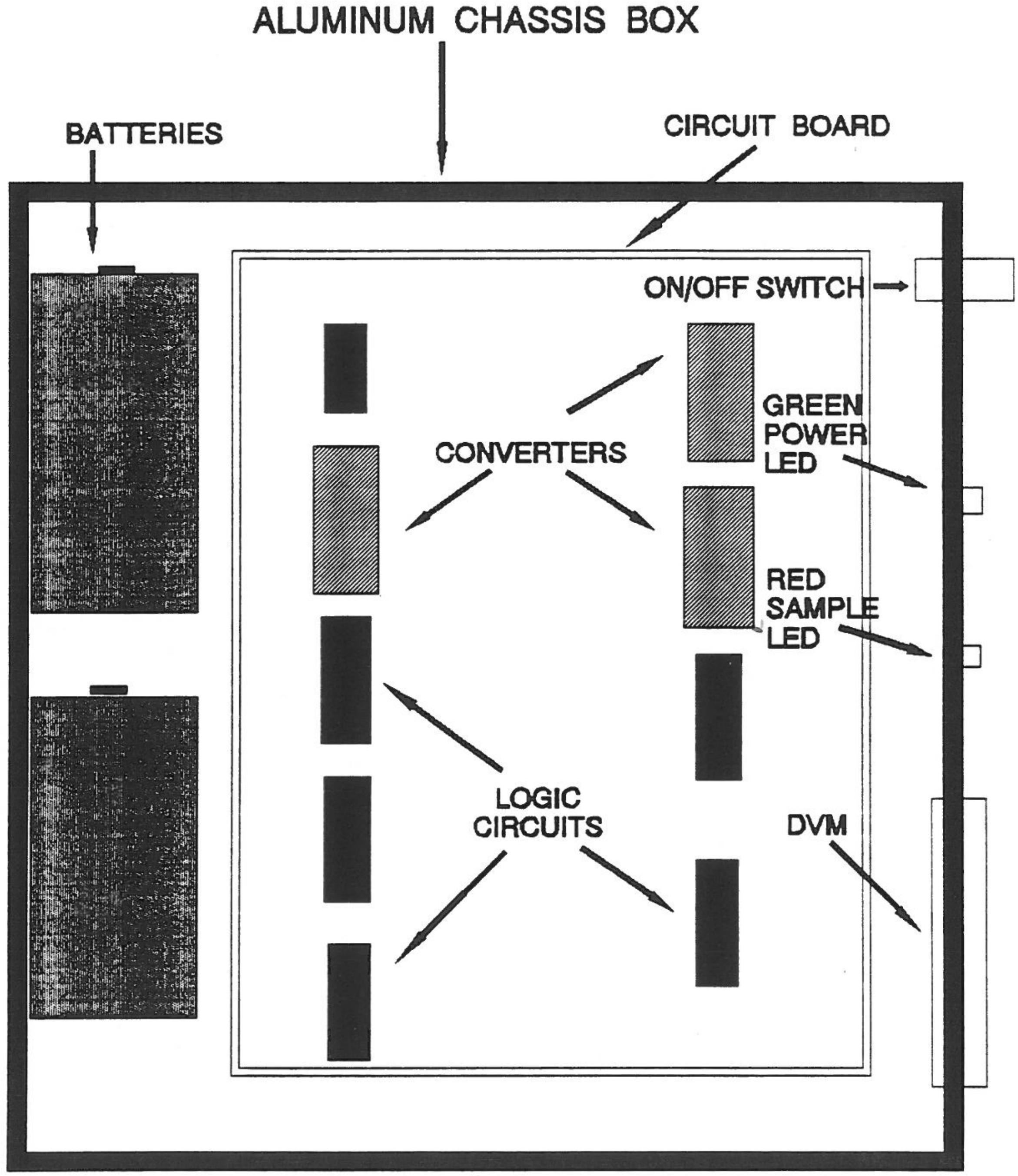
FULL CIRCUIT DIAGRAM



A-1



FRONT PANEL DISPLAY



TOP VIEW OF ELECTROMETER HOUSING

COMPONENT LIST

The following is a list of all the components used to construct the electrometer and their respective manufacturers where applicable. Prices (in parenthesis) are for 1992.

OPA-128	($30)	- *Burr-Brown*
MC74HC4066	($1.24)	- *Motorola*
MC74HC04	($.26)	- *Motorola*
MC74HC4020N	($.98)	- *Motorola*
MC74HC30N	($.64)	- *Motorola*
LM348	($.89)	- *Motorola*
LM555	($.52)	- *Motorola*
DMS-30PC-2-GL	($49)	- *DATEL*
CB3810	($12.65)	- *TDK*
CB3811	($12.65)	- *TDK*
CB3801	($12.65)	- *TDK*
BATTERY HOLDERS	($1.75)	- *Radio Shack*
VICTOREEN - 10^{10} Ω	($25)	- *Victoreen*
Various Resistors		
Various Capacitors		
Connecting Wires		

Word Processing

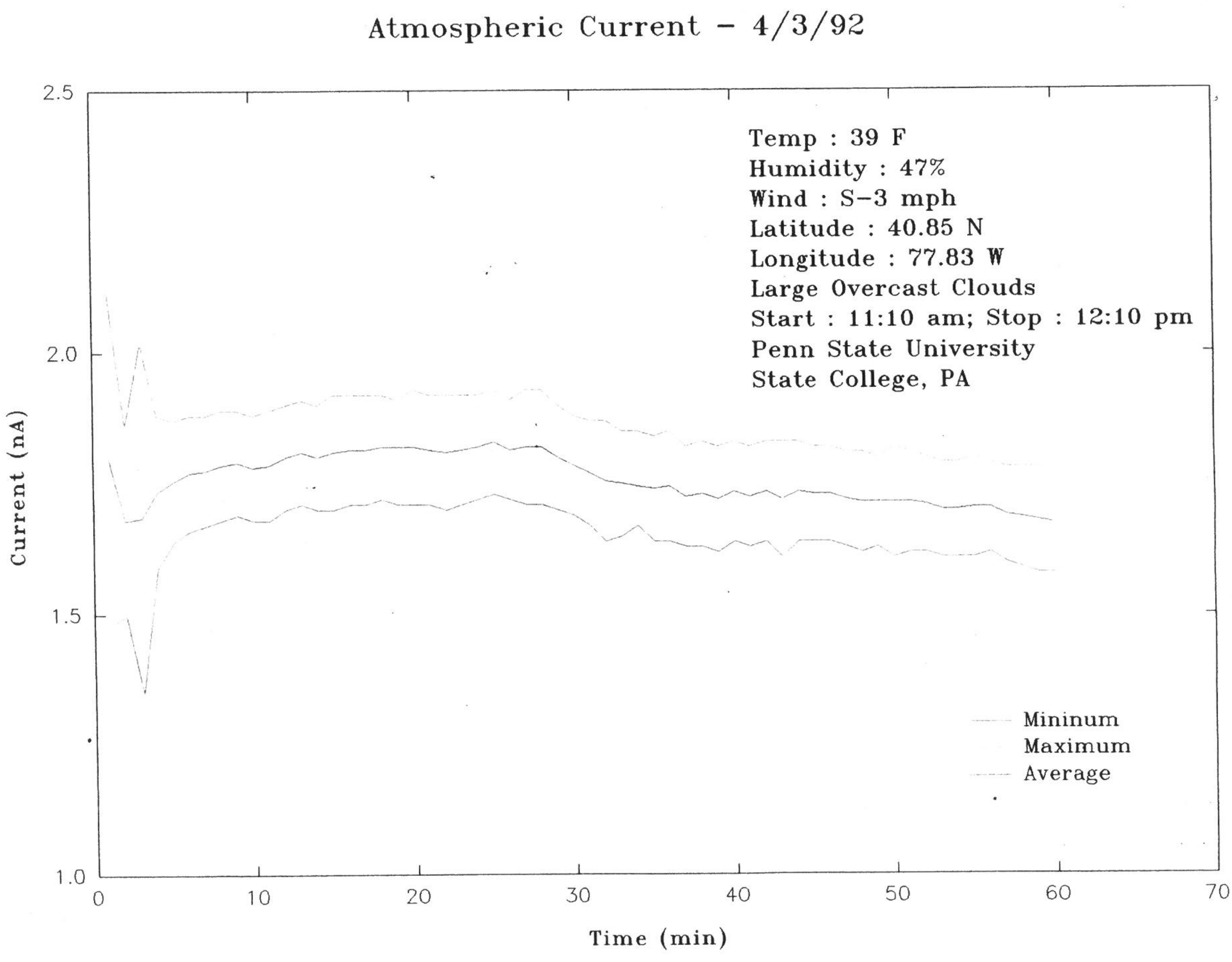
I thought it might be of interest to know what programs and devices were used to write this thesis. I have listed below where and when which programs and devices were used.

All word processing was done using Word Perfect® version 5.1 on IBM compatible PC (microprocessor - INTEL® i486). All equations were written using Equation Writer in Word Perfect®.

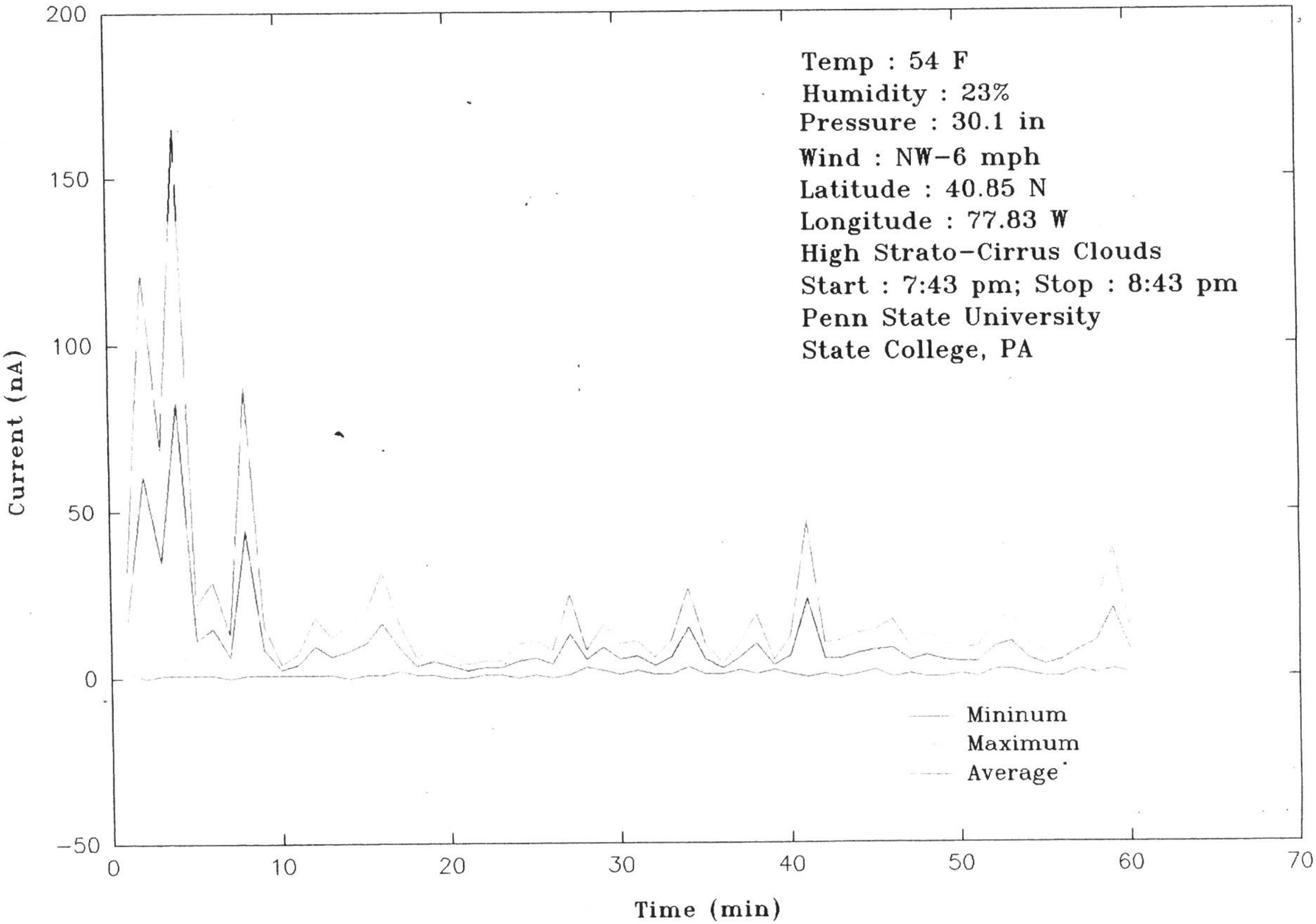
Figures 1 through 5 were incorporated into Word Perfect® for Windows (version 5.1) by using a Hewlett-Packard® ScanJet Plus (version 5.0). The selected image was scanned from its source by the ScanJet and put into the Window's Clipboard. The image was then accessed by Word Perfect® for Windows and pasted in the appropriate place.

Figures 6 through 11 and appendix pages A-1 and A-2 were drawn using Drawperfect®, version 1.1 for IBM compatible PCs.

Plots of data were done using SigmaPlot®, version 4.1 for IBM compatible PCs.


Atmospheric Current - 4/3/92
Current (nA)
2.5
2.0
1.5
1.0
Time (min)
0
10
20
30
40
50
60
70
Temp : 39 F
Humidity : 47%
Wind : S-3 mph
Latitude : 40.85 N
Longitude : 77.83 W
Large Overcast Clouds
Start : 11:10 am; Stop : 12:10 pm
Penn State University
State College, PA
Mininum
Maximum
Average

Atmospheric Current - 4/6/92



References

(1) Handbook of Geophysics and the Space Environment, Fourth Edition, Scientific Editor Adolph S. Jursa, Air Force Geophysics Laboratory, 1985.

(2) Uman, Martin A. and E. Philip Krider,"Natural and Artificially Initiated Lightning",*Science*,**246**:457,27 October 1989.

(3) Barger, Vernon D. and Martin G. Olsson,Classical Electricity and Magnetism: A Contemporary Perspective,(Allyn and Bacon, Inc., Mass., 1987).

(4) Uman, Martin A.,Lightning,(Dover Publications, Inc., New York, 1969).

(5) Radio Shack Enercell Battery Handbook, 1991.

(6) Malan, D.J., and B.F.J. Schonland,An Electrostatic Fluxmeter of Short Response-time for Use in Studies of Transient Field-changes,*Proc. Phys. Soc. (London)*,**B63**:402-408 (1950).

(7) Liu, Wiehsing,A Logarithmic Electrometer For Rocket Probes,The Pennsylvania State University, Department of Electrical and Computer Engineering, June 1991.