DEVELOPING LOW-COST FREQUENCY-DOMAIN ELECTROMAGNETIC
AND INDUCED POLARIZATION GEOPHYSICAL INSTRUMENTATION

by

Gavin Wilson
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Golden, Colorado
Date __________________________

Signed: _________________________

Gavin Wilson

Signed: _________________________

Dr. Jeffrey Shragge
Thesis Advisor

Golden, Colorado
Date __________________________

Signed: _________________________

Dr. Paul Sava
Professor and Department Head
Department of Geophysics
Climate change, expanding populations, and the rapid industrialization of low and middle income countries have created unprecedented challenges for local communities and their surrounding environments. Near-surface geophysical surveying can provide a wealth of data to help address these challenges in a cost-effective manner that is minimally invasive to local environments. Electrical and electromagnetic methods are two such families of techniques that are widely used in near-surface geophysics due to their wide applicability to near-surface problems, such as water exploration and environmental monitoring, the ease of data acquisition, and that electrical and electromagnetic geophysical data can greatly aid near-surface investigations with minimal processing. Recent development and the widespread availability of electrical components and cheap microcomputers have created new opportunities for developing purpose-built, low-cost, open-source geophysical instrumentation for near-surface investigation. This thesis reports the development of two such prototype instruments. First, a frequency-domain instrument that is capable of sensing conductive objects in near-surface environments and costing under US$400 has been designed and validated at the Colorado School of Mines. Second, a time-domain induced polarization instrument, based off an existing low-cost direct current resistivity meter system, was developed and validated in a laboratory setting. The induced polarization system is capable of sensing highly chargeable objects, such as sulfides, and costs under US$200 to construct. Both instruments have demonstrated the capability to be leveraged for near-surface humanitarian applications. Future development includes improving on the mechanical stability of the low-cost instrumentation and improving autologging capabilities for use in remote and time-lapse geophysical investigations.
TABLE OF CONTENTS

ABSTRACT ......................................................... iii
LIST OF FIGURES ............................................... vii
LIST OF TABLES ................................................ xii
LIST OF ABBREVIATIONS ................................. xiii
ACKNOWLEDGMENTS ............................................. xv
CHAPTER 1 INTRODUCTION ................................. 1
  1.1 Low-cost Electromagnetic and Electric Systems .......... 4
  1.2 Thesis Contributions .................................... 5
  1.3 Thesis Outline .......................................... 7
CHAPTER 2 DEVELOPING A LOW-COST FREQUENCY-DOMAIN
  ELECTROMAGNETIC INDUCTION INSTRUMENT ............... 8
  2.1 Abstract .................................................. 8
  2.2 Introduction .............................................. 9
  2.3 Methods ................................................... 11
     2.3.1 FDEM Theory Overview ............................ 11
     2.3.2 Penetration Depth .................................. 13
     2.3.3 Instrument Sensitivity ............................. 14
  2.4 Instrument Design ....................................... 15
     2.4.1 Functionality & Workflow ......................... 16
     2.4.2 Transmitter Design ................................. 17
2.4.3 Receiver Design ..................................................... 20
2.4.4 Construction and Cost Considerations .......................... 21

2.5 Validation ............................................................... 21
2.5.1 Laboratory Validation Tests ..................................... 23
2.5.2 Field Validation Tests ............................................. 26

2.6 Discussion ............................................................... 28
2.6.1 Proof-of-Concept Instrumentation ............................. 28
2.6.2 Future Development ................................................ 30

CHAPTER 3 DEVELOPING A LOW-COST INDUCED POLARIZATION AND
DIRECT CURRENT RESISTIVITY AUTOLOGGING
INSTRUMENT FOR FIELD-SCALE STUDIES ......................... 32

3.1 Introduction ............................................................ 32

3.2 Methods ................................................................. 34
   3.2.1 DC Theory Overview .......................................... 34
   3.2.2 IP Theory Overview ........................................... 37

3.3 Instrument Design ................................................... 40
   3.3.1 Transmitter Design ............................................. 42
   3.3.2 Receiver Design ................................................ 44
   3.3.3 Data recording .................................................. 47
   3.3.4 Construction and Cost Considerations ........................ 48

3.4 Circuit Validation Tests ............................................. 50

3.5 Chargeable Body Validation Tests ................................ 51

3.6 Discussion ............................................................. 55
   3.6.1 Proof-of-Concept .............................................. 55
3.6.2 Future Development ............................................. 57

3.7 Conclusions ......................................................... 58

CHAPTER 4 CONCLUSIONS AND FUTURE WORK .................. 59

4.1 Future Work ............................................................. 60

REFERENCES ............................................................... 62

APPENDIX IP2022 SYSTEM ARDUINO CODE .......................... 68
LIST OF FIGURES

Figure 1.1  Global Climate Risk Index for the period 2000-2019, ranking countries by the amount of extreme weather events, the resulting fatalities, and the economic loss experienced. The index factors in both exceptional climate disasters and extreme weather occurring on an ongoing basis. Such events correspond to resource shortages, destruction of infrastructure, and economic losses. The ten most effected countries are listed above. ................................................................. 2

Figure 1.2  (a) Low-cost FDEM system transmitter module. (b) Low-cost FDEM system receiver module. (c) Low-cost DC resistivity and IP system prototype. ................................................................. 6

Figure 2.1  The magnetic fields resulting from a horizontal coplanar Tx-Rx system configuration over a conductive body. The Tx electronics produce a time-varying current in the Tx coil (blue ring) that generates an alternating magnetic field (solid light gray line) that permeates the air and subsurface. This field will generate eddy currents in conductive subsurface material (orange lines) that create a secondary magnetic field (black dashed lines). The Rx unit measures the combined effects of the time-varying primary and secondary magnetic fields as a voltage. .... 12

Figure 2.2  (a) The absolute value of the Rx voltage measured by a horizontal coplanar (HCP) configuration resting on a halfspace of variable conductivity as a function of Tx-Rx offset. All Rx electronic parameters (resistance, inductance, capacitance, amplifier gain) are as indicated in Figure 4, with a Tx frequency of 1680 Hz, a current of 2.0 A, and Tx and Rx coil areas of 0.29 m$^2$ each with 100 turns. The dashed horizontal lines indicate the upper (9.0 V) and lower (0.1 mV) limits of the Rx amplifier power supply and DMM resolution, respectively. (b) Difference between free-air and half-space voltages (effectively the amplitude of the secondary field) for an HCP configuration with all parameters identical to those shown in (a). ......................... 15
Figure 2.3  (a) Low-cost CSM-EM Tx system powered by two 12 V motorcycle batteries. The RC oscillator generates an AC signal at a given frequency, which is amplified by the power amplifier before being passed into the Tx coil to generate an AC signal and corresponding magnetic field. The DMM measures the alternating current passing through the Tx coil. (b) CSM-EM Tx circuit diagram that can be split into three primary modules: the RC oscillator, the power/signal amplifier, and the Tx coil (with tuning capacitor). The circuit is composed of basic electronic components along with an OPA549 power amplifier breakout board. Resistor \( R_5 \) was included to allow regenerative feedback in the circuit and is not part of a specific Tx module.

Figure 2.4  (a) Low-cost CSM-EM Rx system. The Rx coil (with attached tuning capacitor \( C_{\text{coil}} \)) acts as a LC bandpass filter for a given frequency. The signal is passed through an inverting amplifier and an RMS voltage is measured by a DMM. (b) Low-cost CSM-EM Rx circuit diagram consisting of the Rx coil/tuning capacitor, an OPA741 inverting amplifier powered by two 9 V batteries, and a DMM.

Figure 2.5  CSM-EM Rx signal measured on an oscilloscope using a Rx gain of \( G = 100 \) at a 10 m Tx-Rx offset with (yellow curve) and without (brown curve) introducing a piece of sheet metal near the Rx antenna. The signal with the sheet metal present is less than half the amplitude of that without metal present. The CSM-EM Tx generated the signal for both measurements.

Figure 2.6  Low-cost CSM Rx signal (attached to oscilloscope) using an amplifier gain \( G = 50 \) at a 5 m Tx-Rx offset with the EM34 Tx (brown) and low-cost CSM-EM Tx (yellow). The amplitude of the signal received from the CSM-EM Tx is over twice that of the EM34 Tx.

Figure 2.7  Geometry and results from the CSM-GDL field validation test using a 1.6 kHz Tx frequency. (a) Survey geometry showing the 0.75 m diameter manhole cover surface target located at 18.5 m easting on the test line. The control line is parallel to and 4 m North of the test line. The only other known nearby conductive body is a sprinkler box located close to the survey area. (b) The orange and blue curves show the test line data for the EM-34 Tx and CSM-EM Rx and the CSM-EM Tx and Rx combinations, respectively. Both curves show significant RMS voltage reductions when either the Tx or Rx passes over the target. The green curve presents the control line data unaffected by the surface metal objects. (c) The blue and green curves show CSM-EM Tx current for the test and control lines, respectively. Along the test line, the Tx current dips when the antenna is directly over the manhole cover, as well as at 6.5-7.0 m easting.
Figure 3.1 (a) A simplified expression of DC resistivity measurements using a simple electric circuit. The transmitter system and current measurement is represented by the A and B power source and the ammeter. The receiver module is represented by the voltmeter attached to M and N electrodes. The bulk resistance of the ground is represented by resistor $R_g$. (b) A basic dipole array with the current electrodes A and B on the outside of the array and voltage electrodes M and N at the center of the array. The electrode separation distances $[r_1, r_3, r_2, r_4]$ influence the geometric factor used to calculate apparent resistivity.

Figure 3.2 Five commonly used electrode configuration used for DC resistivity acquisition. The geometric factor $K$ is used with the $\Delta V/I$ ratio to calculate apparent ground resistivity.

Figure 3.3 (a) Current output for both DC and time-domain IP data collection. The current is turned on in the positive direction, cut-off, activated in the reverse direction, and then cut-off again at a set interval. Current reversal prevents electrode polarization. (b) Voltage response from a chargeable subsurface. After the current is activated, the signal will slowly saturate to reach an over-voltage. Once current is cut off, the potential will experience an immediate large drop and then slowly decay. This decay can be measured and integrated to gain an integrated chargeability measurement. (c) Voltage response from nonchargeable subsurface, which is proportional to the current activation and cut-off from the transmitter system.

Figure 3.4 Electrode impedance equivalent circuit for a chargeable subsurface, where $C_{w1}$ represents electrode capacitance, $R_{w2}$ the material resistance, $R_{w1}$ the reaction resistance of the material, and $Z_w$ the Warburg impedance.

Figure 3.5 The entirety of the CSM DCIP2022 system. A 12 V car battery powers a 120 V inverter capable of providing power to the Tx circuit and the Arduino control module. The control module manages the Tx circuit by controlling the relay output pins and measures the resulting voltage through an auto-ranging voltmeter Rx circuit that is based on a multilayered voltage divider design.

Figure 3.6 The Tx circuit design consisting of a bridge rectifier that turns the AC input into a DC signal. Transience within the signal is filtered out by an RC lowpass filter (R6 and C2). Finally, the signal is injected into the ground through electrodes A and B. The relay module attached to A and B controls the current flow through the ground, allowing the user to reverse current to prevent electrode polarization. The current input signal can be measured as a voltage over the shunt resistor $R_s$. 

ix
Figure 3.7  The Rx module consists of a low-pass RC filter to smooth out signal transients. The signal is then passed through a multilayered voltage divider. Optocouplers controlled by the Arduino module act as switches, along voltage to be measured between different resistor combinations, effectively changing the gain of the voltage divider. This protects the ADC chip attached to A0 and A1 in case of large voltages, but allows the chip to maintain accurate measurements when recording small voltage changes.

Figure 3.8  Illustration of the Arduino microcontroller, which manages the Tx current injection and Rx gain. A USB input to the Arduino allows the user to set survey parameters and manually control each measurement made by the DCIP2022 system.

Figure 3.9  (a) Close-up of circuit set-up with a single capacitor attached in parallel with the center resistor. (b) Testing set-up showing the DCIP2022 attached to the circuit, and the 10V DC power source used for current injection.

Figure 3.10  (a) Voltage decay curve 0.1 s after the positive current injection is shut off to avoid the transient behavior. As the capacitance of the circuit increases from 0 µF to 50 µF, the area under the voltage decay curve increases. (b) Voltage decay curve 0.1 seconds after the negative current injection is shut off. A similar trend to (a) can be observed as capacitance increases from 0 µF to 50 µF.

Figure 3.11  (a) An 100 cm long, 45 cm wide, 45 cm deep glass tank is filled with playground sand. The electrodes are set in a Wenner array configuration at 20 cm spacing, buried 4 cm deep. The pyrite body when added to the sand tank was buried in the center (highlighted in blue) directly between M and N at a depth of 10 cm. (b) The iron pyrite was used as an anomalous chargeable body with rough dimensions of 10 cm long, 5 cm wide, and 5 cm high.

Figure 3.12  Tx current recorded from a single duty-cycle measurement over the sand tank without the pyrite sample.

Figure 3.13  (a) Three cycles of data acquired from a single duty-cycle measurement over the sand tank without any pyrite. (b) Four cycles of data from a single duty-cycle measurement over the sand tank with buried pyrite.
Figure 3.14  A zoom-in showing the decay curves (a) after the positive current cut-off (cycle time 6.0-9.0 s) and (b) after the negative current cut-off (cycle time 12.0-15.0 s). The typical decay curve shape cannot be visually observed due to the large effects of the counter-electromotive force from current cut-off.
LIST OF TABLES

Table 2.1  Cost breakdown (in USD) for parts required to construct and operate the system. Note that this estimate assumes all products are bought new. Many components (especially wire) can be repurposed, allowing the system to be built at a lower overall cost. ................................. 23

Table 3.1  Approximate cost breakdown (in USD) for parts required to construct and operate the system. Wires, electrodes, and battery power source are not included due to being required components for all DC/IP systems. Materials such as wires and general-purpose resistors may be priced lower than suggested above. ............................................. 49

Table 3.2  Calculated integrated chargeability for each half-duty cycle, as well as the differences between the calculated average chargeability with and without the pyrite body present for the positive half-duty cycle (6.1-9.0 s) and the negative half-duty cycles (12.1-15.0 s). Measurement uncertainty 0.1 mV for the receiver, and is detailed in the Receiver Design. ............................... 55
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>Alternating current</td>
<td>AC</td>
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<tr>
<td>Analog-Digital Converter</td>
<td>ADC</td>
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<tr>
<td>Colorado School of Mines</td>
<td>CSM</td>
</tr>
<tr>
<td>Colorado School of Mines Electromagnetics System</td>
<td>CSM-EM</td>
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<tr>
<td>DC/IP 2022 system</td>
<td>DCIP2022</td>
</tr>
<tr>
<td>Dana Sirota 2020</td>
<td>DS2020</td>
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<tr>
<td>Digital Multimeter</td>
<td>DMM</td>
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<td>Direct current</td>
<td>DC</td>
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<tr>
<td>Frequency-domain electromagnetics</td>
<td>FDEM</td>
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<tr>
<td>Geophysical Discovery Lab</td>
<td>GDL</td>
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<tr>
<td>Geoscientists without Borders</td>
<td>GWB</td>
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<tr>
<td>Induced polarization</td>
<td>IP</td>
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<tr>
<td>Inductor-Capacitor</td>
<td>LC</td>
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<tr>
<td>Non-governmental organization</td>
<td>NGO</td>
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<td>One-dimensional</td>
<td>1-D</td>
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<tr>
<td>Receiver</td>
<td>Rx</td>
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<tr>
<td>Resistor-Capacitor</td>
<td>RC</td>
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<tr>
<td>Spontaneous Potential</td>
<td>SP</td>
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<tr>
<td>Three-dimensional</td>
<td>3-D</td>
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<td>Transmitter</td>
<td>Tx</td>
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Two-dimensional
ACKNOWLEDGMENTS

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CHAPTER 1
INTRODUCTION

Climate change and rapidly expanding populations have created unprecedented challenges for communities around the globe. Many low and middle-income communities (LMICs) lack capital to address such hazards, making them particularly susceptible to humanitarian challenges such as insufficient access to drinking water [1], devastating landslides [2], and environmental pollution [3]. The rapid industrialization and population growth of many LMICs increases both the severe and persistent nature of environmental hazards and resource shortages. According to the United Nations Department of Economic and Social Affairs, the number of urban residents in poor countries will likely increase by 1.0 billion to more than 2.5 billion by 2050, with Sub-Saharan Africa and South Asia contributing to the majority of the increase [4]. The annual Global Climate Risk Index showed that these regions are at severe risk from agricultural productivity loss, sea level rise, and extreme weather (see, e.g., Figure 1.1 [5]). Solving these challenges requires addressing both the technical and socio-economic barriers faced by vulnerable communities. The United Nations [6] and World Bank [7, 8] have prioritized initiatives to combat resulting food and water shortages through community education, agricultural management, and sustainable water exploration and usage. Addressing these issues relies on the prioritization of environmental hazard mitigation as well as having accurate and readily accessible and timely information on local natural resources, which both requires and motivates the use of techniques appropriate for consistent environmental and subsurface monitoring.
Figure 1.1 Global Climate Risk Index for the period 2000-2019, ranking countries by the amount of extreme weather events, the resulting fatalities, and the economic loss experienced. The index factors in both exceptional climate disasters and extreme weather occurring on an ongoing basis. Such events correspond to resource shortages, destruction of infrastructure, and economic losses. The ten most effected countries are listed above.

Near-surface geophysical surveying and monitoring can provide a wealth of geotechnical, resource, and natural hazard data through a variety of different techniques that can be tailored to specific community challenges. While direct conventional ground investigation methods such as drilling or excavation can be expensive, time intensive, and invasive, applied geophysical techniques are able to acquire data about subsurface properties in a non-invasive and cost-effective manner. Near-surface geophysics is a well-established tool for groundwater prospecting [9–14] and time-lapse monitoring for environmental studies [15, 16]. Near-surface geophysical methods have also been applied for the purposes of infrastructure monitoring [17] and archaeological reconnaissance.
[18, 19], among others. There are also a variety of nongovernmental aid organizations (NGOs), such as Geoscientists Without Borders (GWB) [20–22] and Thriving Earth Exchange [23, 24], that focus on using applied geophysical methods to address the aforementioned community-focused sociotechnical challenges.

Although near-surface geophysics has experienced growth in industrial and academic applications, there is a significant upfront cost of procuring applied geophysical equipment, a fact that effectively forms a “barrier-to-entry” for many potential users. The equipment expense is primarily due to the design parameters of most commercial instruments, which are engineered to acquire high-quality data under extreme environmental conditions and possibly over an extended survey duration. While this is important for many industrial and research applications, such instrument features are not necessarily required and may be “over-engineered” for small-scale near-surface geophysical applications.

Recent developments in low-cost microcomputers and sensors along with the wide availability of basic electronic components and open-source software packages have allowed novices and experts alike to build highly accurate sensor systems at affordable prices and reasonable precision for small-scale research and enthusiast projects. These tools can be leveraged to develop low-cost, purpose-built geophysical equipment that be used to acquire data without exceeding budgetary constraints that prevent many users from using commercial-grade geophysical equipment. Examples from recent years include for water exploration using low-cost direct-current (DC) resistivity [20, 25, 26], seismometer [27–30], and magnetometer [31–33] systems. While low-cost instruments may lack the durability and many of the quality-of-life features present in commercial instruments, they can significantly lower the economic barrier-to-entry for many potential users and be used in small-scale near-surface geophysical investigations. Much of the work presented in this thesis is motivated by this paradigm and seeks to make a contribution to the growing applied geophysics community who are interested in the development and application of low-cost electromagnetics and electrical instrumentation.
1.1 Low-cost Electromagnetic and Electric Systems

Electromagnetic and electrical methods are of particular interest for near-surface and more specifically humanitarian applications due to their versatility and ease of use. Surveys using the principles of frequency-domain electromagnetics (FDEM) are straightforward to execute for small teams over large areas, making them ideal for small-scale projects and with low capital requirements. FDEM instruments are used in near-surface geologic characterization, reconnaissance surveys, and environmental monitoring, making them a powerful tool for a wide variety of humanitarian applications. Similarly, DC resistivity and induced polarization (DC/IP) instruments are widely used for groundwater characterization, resource prospecting, and pollutant monitoring, which represent common applications in humanitarian-based geophysical investigations. In addition, data acquired with these methods require little processing to gain valuable information, with initial EM results often being interpretable without data inversion and DC/IP data rarely requiring data processing beyond inversion for most near-surface applications. This feature further motivates the use of these methods by non-specialist applied geophysics technicians who are trained to use the instruments and interpret the data for understanding subsurface geology with regard to, e.g., availability of groundwater resources.

FDEM is important for near-surface applications because of its sensitivity to subsurface variations in electrical resistivity originating due to, e.g., geological heterogeneity or variable fluid saturations. FDEM surveying is based on the principle of electromagnetic induction and requires only one or two operators to acquire data. FDEM instruments do not have to be attached to the earth unlike grounded methods (e.g., DC resistivity, induced polarization, and seismic), which allows users to acquire spatial FDEM data at faster rates than comparable ground-coupled methods. FDEM has a history of being used for geological characterization [34], waste monitoring [35], irrigation management [21], and archaeological reconnaissance [19]. Thus, developing a low-cost FDEM system could allow for a limited number of people to quickly perform geophysical reconnaissance on areas of
interest before using more time-consuming methods (e.g., DC resistivity or seismic) for more spatially focused investigations or before investing in significantly more expensive excavation and/or drilling operations.

DC resistivity and induced polarization (IP) methods, developed in the early 1900s [36], are two of the most widely used and reliable geophysical techniques for sensing subsurface fluids. DC/IP data typically require minimal processing, and geophysical inversions can be conducted with a large variety of open-source geophysical inversion software packages such as SimPEG [37], pyGIMLI [38], and ResIPy [39]. Examples of recent low-cost projects include DC resistivity sounding instruments capable of locating and characterizing groundwater resources using basic electrical components and off-the-shelf digital multimeters [20, 25]. Other efforts have focused on developing laboratory-scale DC resistivity devices capable of multichannel measurements and digital autologging with the aid of Arduino microcontrollers [26, 40]. Engineering a field-scale low-cost instrument capable of digital data acquisition would both speed up geophysical data collection and open up opportunities for remote time-lapse geophysical monitoring. Examples of studies in this direction include groundwater and environmental monitoring [41, 42] along with geohazard preparedness [43]. Dense data sampling and minimal software changes would also allow low-cost instrument to easily acquire IP chargeability information, which opens up the possibility of low-cost time-lapse subsurface monitoring for many environmental pollutants.

1.2 Thesis Contributions

The key goals of this thesis are to develop and validate two low-cost prototype geophysical instrumentation systems capable of acquiring amplitude-based FDEM data and DC/IP data, respectively. The design goals of the FDEM system (Figure 1.2a and Figure 1.2b) are to demonstrate sensitivity to shallow conductive objects using amplitude-based measurements, to keep fabrication costs under US$500, and to ensure instrument functionality at field-scale transmitter-receiver (Tx-Rx) offsets. The design
goals of the low-cost DC/IP system (Figure 1.2c) are to integrate previously existing low-cost DC resistivity equipment designs with microcomputers and low-cost sensors to develop a device capable of acquiring time-domain IP data in time-lapse surveys and to keep fabrication costs under US$300. A final overall project goal is to validate both prototypes and determine their viability (and future system iterations) for small-scale near-surface geophysical investigation.

Figure 1.2 (a) Low-cost FDEM system transmitter module. (b) Low-cost FDEM system receiver module. (c) Low-cost DC resistivity and IP system prototype.

As part of this thesis work, I tested FDEM system in a laboratory setting to examine the instrumental functioning frequency as well as its ability to detect conductive objects. This system was also tested outdoors at field-scale Tx-Rx offsets in CSM Geophysical Discovery Lab (GDL) over a conductive object, with the data being successfully comparable to those acquired using a commercial-grade FDEM transmitter. The DC/IP autologging instrument was validated against a commercial instrument in laboratory sand tank experiments using different chargeable materials.
1.3 Thesis Outline

This thesis is divided into four chapters, the first of which being the current
Introduction. Chapter 2 presents a brief overview of the FDEM method, an examination of
the prototype CSM-EM system design, and discussions of validation testing results and
future potential research directions of the system. This chapter has been submitted as the
following manuscript:

- Wilson, G., J. Conrad, J. Anderson, A. Swidinsky, and J. Shragge, 2022, Developing
  a Low-cost Frequency-domain Electromagnetic Induction Instrument, submitted to
  The Journal of Geoscientific Instrumentation, Methods and Data Systems.

Chapter 3 begins with an overview of DC resistivity and time-domain IP methods and the
design of the low-cost DC/IP autologging system. I then present the instrument validation
testing results and review the successes and limitations of the developed system. This
chapter is being prepared for submission as the following manuscript:

- Wilson, G., J. Shragge, R. Krahenbuhl, A. Swidinsky, 2022, Developing a Low-cost
  Induced Polarization Instrument for Earth Science Applications, to be submitted to
  The Journal of Geoscientific Instrumentation, Methods and Data Systems.

Chapter 4 presents the overall project conclusions, suggestions for future instrumentation
improvements, and potential uses of the developed low-cost equipment for humanitarian
geophysics applications.
CHAPTER 2
DEVELOPING A LOW-COST FREQUENCY-DOMAIN ELECTROMAGNETIC INDUCTION INSTRUMENT

Modified from a paper under review in *The Journal of Geoscientific Instrumentation, Methods and Data Systems.*

2.1 Abstract

Recent advancements and the widespread availability of low-cost microcontrollers and electronic components have created new opportunities for developing and using low-cost, open-source instrumentation for near-surface geophysical investigations. Geophysical methods that do not require ground contact, such as frequency-domain electromagnetics, allow one or two users to quickly acquire large amounts of ground resistivity data. The Colorado School of Mines electromagnetic system (CSM-EM) is a proof-of-concept instrument capable of sensing conductive objects in near-surface environments, is similar in concept to commercial-grade equipment, and costs under US$400 to build. We tested the functionality of the CSM-EM system in a controlled laboratory setting during the design phase and validated it over a conductive target in an outdoor environment. The transmitter antenna can generate a current of over 2.5 A, generating signals that are detectable by a receiver antenna at offsets of up to 25 m. The system requires little refitting to change the functioning frequency, and has been operationally validated at 0.4 kHz and 1.6 kHz. The receiver signal can be measured by off-the-shelf digital multimeters. Future directions will focus on improving the electronic and mechanical stability of the CSM-EM with the goal of using acquired data to make quantitative estimates of subsurface resistivity distribution.
2.2 Introduction

Near-surface geophysical surveying using electrical and electromagnetic (EM) methods has experienced growth in recent years due to increased interest in identifying groundwater resources [44], addressing environmental remediation [35], and performing archaeological reconnaissance studies [19]. Near-surface geophysical techniques provide non-invasive and cost-effective approaches for imaging subsurface structures and estimating earth properties, compared to methods such as drilling or excavation [45]. Additional near-surface EM application examples include using conductivity data combined with soil sampling and satellite imagery to develop frameworks for farm irrigation management [21]; applying EM methods for environmental remediation to assess the location and areal extent of pollutants including landfills and radioactive waste disposal sites [35]; and developing lightweight drone-based EM systems for detecting and classifying unexploded ordinance [46], which opens up opportunities for drone-based EM surveying in environmental and agricultural applications.

While geophysical methods can assist with subsurface investigations, the cost of commercial instruments required to perform such surveys can be prohibitively expensive and form an effective “barrier to entry” for many potential users. The price constraints of many commercial grade instruments stem from their hardware being designed for large-scale campaigns, industrial applications, and the capability to acquire high-quality data under extreme climate conditions (e.g., from the frozen Arctic to the hot desert). This leads to scenarios where commercial instruments are effectively “over-engineered” for many near-surface geophysical applications, when more elementary instrumentation and data acquisition procedures would suffice.

The recent rapid growth of low-cost microcontrollers (e.g., Arduino and Raspberry Pi) and sensors as well as the proliferation of open-source software packages allow entry-level and expert practitioners alike to build high-accuracy sensor systems at a price range affordable for small-scale research and enthusiast projects. These tools have the potential
to be leveraged in purpose-built low-cost geophysical equipment that can acquire data without exceeding the durability and budgetary constraints for many types of near-surface geophysical investigations. Examples following this low-cost instrumentation approach include direct-current (DC) resistivity [20, 25, 26], seismic nodes [27–29], and magnetometers [31, 32], each of which has demonstrated the possibility of acquiring data of comparable quality to commercial grade systems. While such home-grown instrumentation is neither as robust nor as likely to have the in-built safety factors as commercial grade instruments, it can lower the barrier-to-entry for many users, enable enthusiast or humanitarian geoscience applications, and be used to develop low-cost geophysical networks for time-lapse monitoring projects.

Frequency-domain electromagnetic methods (FDEM) represent a class of geophysical techniques that are important for near-surface applications due to their sensitivity to subsurface variations in electrical resistivity (or its inverse, electrical conductivity) due to, e.g., heterogeneity in geological material or variable fluid saturations. FDEM surveying is based on the principle of electromagnetic induction and requires only one or two operators to acquire data, meaning that the instrument does not have to be attached to the earth unlike grounded methods (e.g., DC resistivity, induced polarization, and seismic). This advantage allows users to acquire spatial FDEM geophysical data at greater rates than comparable ground-coupled methods, and furthermore makes the approach a strong candidate for EM drone-receiver based investigations. Overall, developing a low-cost FDEM system prototype that provides accurate data could create significant opportunities for numerous near-surface geophysical applications.

The primary goal of this study is to design, build and validate a low-cost transmitter-receiver FDEM system for under US$500. Our developed proof-of-concept instrument, the CSM-EM, is of comparable size and transmits similar signal strength to the commercial Geonics EM-34 system, and can detect conductive objects using amplitude-based signal measurements via an autoranging digital multimeter (DMM). The
instrument is straightforward to operate and can function at a variety of transmitter/receiver frequencies with minimal refitting. The paper starts by briefly describing the theory behind the FDEM method and its use in geophysical investigations. We then discuss our low-cost FDEM transmitter-receiver system design and provide details on its construction. We conclude by presenting validation results for the system prototype in both laboratory and outdoor conditions, and by discussing the cost breakdown and future refinements of the device, along with possible applications in near-surface geophysical investigations.

2.3 Methods

The purpose of this section is to provide a brief review of the theoretical principles and some methodological considerations behind the FDEM technique. Readers interested in a more complete theoretical treatment are referred to standard reference texts on these subjects [45], [47].

2.3.1 FDEM Theory Overview

Electromagnetic methods measure ground resistivity through EM induction with separated transmitter (Tx) and receiver (Rx) antennas, allowing data acquisition without the need for ground contact. As detailed in the Instrument Design section below, the two antennas are circular coils of wire connected to different electronic modules. FDEM methods are based upon the principles of Ampere’s and Faraday’s Laws in a quasi-static regime, where an alternating current (AC) produces a magnetic field and an alternating magnetic field produces an electric field, respectively. As illustrated in Figure 2.1, FDEM uses a known and calibrated time-varying current in the Tx coil (blue loop) to produce an alternating primary magnetic field that is present in both the air and subsurface (solid gray lines). This field operates at a single frequency specified by the user. For scenarios involving conductive subsurface material, this alternating magnetic field will induce alternating eddy currents (orange lines) via Faraday’s Law. As described by Ampere’s Law, these eddy
currents produce a secondary magnetic field (dashed black lines). The superimposed fields produce a time-varying current in the Rx coil (red loop), as per Faraday’s Law. This signal will oscillate at the same frequency as the field generated by the Tx and can be measured as a voltage drop across a capacitor attached in series with the Rx antenna coil.

Figure 2.1 The magnetic fields resulting from a horizontal coplanar Tx-Rx system configuration over a conductive body. The Tx electronics produce a time-varying current in the Tx coil (blue ring) that generates an alternating magnetic field (solid light gray line) that permeates the air and subsurface. This field will generate eddy currents in conductive subsurface material (orange lines) that create a secondary magnetic field (black dashed lines). The Rx unit measures the combined effects of the time-varying primary and secondary magnetic fields as a voltage.

When the system is over a uniform halfspace of a given conductivity, a Tx-Rx configuration with a fixed offset and orientation will measure a constant voltage independent of lateral position. However, the presence of lateral subsurface heterogeneities will affect the signal detected by the Rx and introduce spatial dependence in the voltage measurements. This makes FDEM particularly effective at identifying lateral changes in soil-water content and at locating anomalous conductive bodies (such as illustrated in Figure 2.1). Some commercial EM systems also use a tuneable third “bucking” coil to remove the primary field response from the Rx coil, due to the large amplitude of the primary field compared to that of the secondary field (the latter of which contains the
relevant information about ground conductivity).

2.3.2 Penetration Depth

The penetration depth of any EM method is dependent upon a variety of subsurface physical properties and the frequency of the inducing magnetic field produced by the Tx. For FDEM field applications, the effect of these properties can be quantified using a proxy value known as the skin depth $\delta$

$$\delta = \frac{1}{\sqrt{\pi \mu \sigma f}}, \quad (2.1)$$

which represents the depth in the subsurface at which the field strength has decayed to $1/e$ (37%) of the surface value. Skin depth is inversely proportional to the square root of the subsurface electrical conductivity $\sigma$, magnetic permeability $\mu$, and the operating frequency of the instrument, $f$. Electrical conductivity is related directly to subsurface geological structure, as well as any fluids that might be saturating the associated pore space. In most geological situations, the magnetic permeability $\mu$ can be assumed to equal the magnetic permeability of free space $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$. This leaves frequency as the only tuneable experimental variable in a given survey, meaning that the depth of investigation can be increased or decreased by respectively decreasing or increasing the Tx frequency, along with Tx-Rx offset.

While the frequency of the EM system can be used to alter the penetration depth of the inducing fields, different relative orientations of the Tx and Rx coils can be used to change the EM field radiation patterns and achieve different subsurface sensitivities. ?? illustrates three common Tx-Rx “fully coupled” orientations, with the horizontal coplanar (HCP) being the most common investigation setup and the one used in the validation tests reported herein.

The Tx-Rx offset $r$ has a major effect on signal decay. For a uniform halfspace of conductivity $\sigma$ and an HCP configuration, the signal of frequency $f$ is related to the vertical magnetic field strength detected by the Rx coil [45, Eq. 4.56]. Changes in the vertical
magnetic field can be measured as a voltage by the Rx, $V_R$, and is related to offset $r$ by

$$
V_R = \frac{if\mu_0 A_T A_R N_T N_R I_T}{k^2 r^5} \left[ 9 \left( 9 + 9i kr - 4k^2 r^2 + -ik^3 r^3 \right) e^{-ikr} \right],
$$

(2.2)

where $k = \sqrt{-i\sigma_0 2\pi f}$, $I_T$ is the Tx current, and $A_T$, $A_R$, $N_T$, and $N_R$ respectively are the areas and the number of wire turns around the Tx and Rx antennas. While $f$, $k$, and $r$ solely account for the magnetic field strength at the Rx coil in an HCP Tx-Rx orientation, $I_T$, $A_T$, $A_R$, $N_T$, and $N_R$ (Tx/Rx component parameters) affect both the magnetic field strength, and the value measured across Rx by a DMM.

### 2.3.3 Instrument Sensitivity

The choice of component parameters (i.e., the effective areas of the Tx and Rx antennas) were based off of the dimensions of the EM-34 conductivity meter due to its in-house availability and large size. Before building the prototype, the antenna parameters were tested by modeling the Rx voltage over a range of half-space resistivity values to determine whether the CSM-EM range and resolution (0.1 mV-9.0 V) allowed the instrument to delineate between different geologic environments. This testing modeled the change in Rx signal, which measures the strength of the total vertical magnetic field, over a half space as a function of Tx-Rx offset (Figure 2.2a). We also examined how the secondary field, containing the information related to ground resistivity, changed with variable resistivity for a range of Tx-Rx offsets (Figure 2.2b). The total field voltage response modeling (i.e., the value measured by the instrument) shows that signals over different half-space resistivity values fall within CSM-EM resolution for most offsets from 1 m to 50 m. The only half-space resistivity falling outside the CSM-EM resolution was the simulated perfect conductor ($\sigma = 10^6$ S/m). This exercise demonstrated that the effect of the secondary field is difficult to detect for most half-space resistivities. The secondary field response showed whether different half-space resistivities could be delineated given the resolution of the CSM-EM system. The secondary field was calculated by subtracting the primary (free space) field from the total field. This calculation showed that subsurface
resistivity variations ranging from $10^0 \, \Omega \cdot m$ to $10^2 \, \Omega \cdot m$ would be detectable within the CSM-EM resolution at most Tx-Rx offsets. However, more resistive environments (e.g., $10^3 \, \Omega \cdot m$) would generate an insufficient secondary field to create a voltage change detectable by the CSM-EM, given that most DMMs measure voltages to within a ±0.1 mV precision.

![Graphs showing Rx voltage and voltage difference](image)

Figure 2.2 (a) The absolute value of the Rx voltage measured by a horizontal coplanar (HCP) configuration resting on a halfspace of variable conductivity as a function of Tx-Rx offset. All Rx electronic parameters (resistance, inductance, capacitance, amplifier gain) are as indicated in Figure 4, with a Tx frequency of 1680 Hz, a current of 2.0 A, and Tx and Rx coil areas of 0.29 m$^2$ each with 100 turns. The dashed horizontal lines indicate the upper (9.0 V) and lower (0.1 mV) limits of the Rx amplifier power supply and DMM resolution, respectively. (b) Difference between free-air and half-space voltages (effectively the amplitude of the secondary field) for an HCP configuration with all parameters identical to those shown in (a).

### 2.4 Instrument Design

The primary goals in the design of the low-cost CSM-EM FDEM system are to: (1) construct an adaptable device able to function at multiple signal frequencies and Tx-Rx offsets similar to commercial FDEM instrumentation; (2) use basic and easily sourced electrical components; and (3) maintain a sub-$500 instrument build cost. While the use of low-cost components sacrifices some of the durability found in commercial systems, easily procurable components facilitate replacement or even the construction of multiple EM
systems to work independently or jointly and at a low capital expenditure.

The design goals for the low-cost CSM-EM device require that the Tx-Rx frequency can adjust with minor hardware changes and that the CSM-EM Tx signal is comparable in strength to that offered by a commercial FDEM system Tx. The Geonics EM-34 conductivity meter system was chosen as the basis for the CSM-EM design due to in-house availability and its depth-of-investigation relevant to near-surface applications.

2.4.1 Functionality & Workflow

The CSM-EM instrument is composed of independent Tx and Rx units. During data acquisition, the Tx hardware module generates an AC signal that is amplified and transmitted through the Tx antenna. Both the primary EM field from the Tx unit and secondary fields generated by conductive subsurface heterogeneity are measured by the Rx antenna. The composite signal is filtered and then amplified so that voltage changes can be sensed with a 0.1 mV resolution DMM (Figure 2.2 shows the system resolution limits) capable of measuring AC signals. The multimeter records an approximate root-mean-squared (RMS) voltage, which is a simple measure of the signal magnitude generated by the primary Tx field and any secondary EM fields. The design and functionality of the Tx and Rx units are described below. The specific component values represented in CSM-EM design can be easily modified and are based on the calibrated inductance and resistances of the Tx and Rx coils. The resistances of the coils were measured using a DMM. Coil inductances were measured by using a known capacitor in series with the coil to create an LC circuit, scanning through a range of input frequencies until achieving resonance in the coil, and finally back-solving for coil inductance ($L_{coil}$) using equation 2.5. By tailoring component values to the Tx and Rx properties, the CSM-EM can be constructed using easily substituted parts.
2.4.2 Transmitter Design

The series of hardware modules of the CSM-EM Tx unit and the circuitry design behind each module are presented in Figure 2.3a and Figure 2.3b, respectively. The RC oscillator and power amplifier modules are powered by two 12 V motorcycle batteries. Alternatively, the system could be powered by four 12 V batteries with two pairs connected in series to obtain a larger Tx current; however, following this approach may shorten instrument longevity in the field.

The Tx system generates an AC signal using a resistor-capacitor (RC) oscillator module. An RC oscillator generates an AC signal using EM noise, RC circuit feedback, and signal amplification [48]. Any EM noise encountered by the module is filtered through several RC stages that introduce a phase shift at a given angle depending on the chosen RC component values and the number of stages \( N_S \) within the circuit. The cumulative RC signal conditioning creates a 180° phase shift. The resulting signal is subsequently amplified by an inverting operational amplifier, which causes another 180° phase shift. This shift creates regenerative feedback, allowing for a stronger AC signal to be generated solely from ambient EM fields and a DC power source. The desired frequency \( f_{RC} \) (in Hz) of the AC signal can be calculated using

\[
f_{RC} = \frac{1}{2\pi RC \sqrt{2N_S}},
\]

(2.3)

where \( R \) is resistance, \( C \) is capacitance, and \( N_S \) is the number of RC stages. The \( R \) and \( C \) components in each stage of the RC oscillator must have the same respective resistance and capacitance values, meaning that in Figure 2.3b \( R = R_1 = R_2 = R_3 \) and \( C = C_1 = C_2 = C_3 \). RC oscillators commonly have three RC stages to maintain signal stability [48], which is reflected in our CSM-EM oscillator module. Representative values of \( C = 1.8 \) nF, \( R = 22.0 \) kΩ, with \( N_S = 3 \) generate an \( f_{RC} = 1.64 \) kHz. The output frequency of the CSM-EM system can be modified by switching out modular capacitor units with differing \( C \) values and changing the tuning capacitor attached to the Tx antenna.
Figure 2.3 (a) Low-cost CSM-EM Tx system powered by two 12 V motorcycle batteries. The RC oscillator generates an AC signal at a given frequency, which is amplified by the power amplifier before being passed into the Tx coil to generate an AC signal and corresponding magnetic field. The DMM measures the alternating current passing through the Tx coil. (b) CSM-EM Tx circuit diagram that can be split into three primary modules: the RC oscillator, the power/signal amplifier, and the Tx coil (with tuning capacitor). The circuit is composed of basic electronic components along with an OPA549 power amplifier breakout board. Resistor $R_5$ was included to allow regenerative feedback in the circuit and is not part of a specific Tx module.

The stability of the signal output also depends on the applied amplifier gain. Gain is a unitless value that describes the ratio between the voltage of the output signal from an operational amplifier (op-amp) to that of the input signal. The signal gain $G$ of the output
voltage $V_{out}$ is dependent on the values of resistors $R_f$ and $R$ attached to the op-amp and on the voltage of the input signal $V_{in}$, as follows for a simple inverting amplifier:

$$V_{out} = GV_{in} = -V_{in} \left( \frac{R_f}{R} \right).$$

(2.4)

Figure 2.3b uses this setup within the RC oscillator assembly with a gain $G = 31$, which is controlled by resistors $R = R_3$ and $R_f = R_4$ in Figure 2.3b. The op-amp gain of an RC oscillator must be $G \geq 29$ to main signal stability [48]; however, a value $G \gg 29$ tends to distort the AC signal.

The small AC signal generated by the RC oscillator is impractical at any field scale Tx-Rx offset [48]. The high-voltage, high-current op-amp device (OPA549) can supply a current up to 8.0 A to any load attached to the output. The OPA549 has been driven to saturation as a $\pm 12$V square wave, the maximum signal gain allowable by the power supplies, and does not follow equation 2.4. This specialized power amplifier is required for signal amplification needed to generate measurable field-scale signals. The power amplifier is part of a pre-fabricated breakout board with DC power supply regulating capacitors and a heat sink. We initially built a heat sink attachment in-house (central unit in Figure 2.3b), but the pre-fabricated unit (power amplifier in Figure 2.3a) proved to be safer, more durable, and reliable under field conditions.

Finally, the amplified signal is passed into the Tx antenna, consisting of 100 turns of wire around a 0.61 m (2 ft) diameter coil. To generate resonance in the Tx coil at the same frequency as the RC oscillator, we must include a tuning capacitor [48]. The resulting RLC circuit uses a capacitor $C_{coil}$ and the inherent inductance $L_{coil}$ of the Tx antenna to provide an effective bandpass filter. The filtered output frequency $f_{coil}$ is inversely proportional to the square root of the $L_{coil}C_{coil}$ product:

$$f_{coil} = \frac{1}{2\pi \sqrt{L_{coil}C_{coil}}}. \quad (2.5)$$

The Tx antenna had a measured inductance of $L_{coil} = 13.28$ mH that when combined with a $C_{coil} = 770$ nF tuning capacitor created a bandpass filter with a peak frequency of
$f_{\text{coil}} = 1.57 \text{ kHz}$. The LC circuit ensures that when the square-wave signal passes through the LC circuit, it is transmitted as a monochromatic sinusoidal wave. Although LC filters theoretically pass a single frequency, the Tx wire itself has a fixed resistance value; when combined with the LC filter inductance $L_{\text{coil}}$, the resistance $R_{\text{coil}}$ dictates the filter pass-band width $\Delta f_{\text{width}}$ (i.e., the frequency range about the peak value that is still passed through the filter). Whereas too broad of a pass band would weaken the resonance of the Tx antenna, too narrow of a pass band may decrease the signal strength at frequencies close to, but not exactly at, the peak frequency. This poses a significant challenge because low-cost hardware components are often imprecise. The pass-band width is proportional to the ratio of the Tx wire resistance $R_{\text{coil}}$ and inductance $L_{\text{coil}}$ values:

$$\Delta f_{\text{width}} = \frac{1}{2\pi} \frac{R_{\text{coil}}}{L_{\text{coil}}}.$$  

(2.6)

Because the CSM-EM instrument Tx coil has an inductance of $L_{\text{coil}} = 13.28 \text{ mH}$ and a resistance of $R_{\text{coil}} = 3.2 \text{ Ohms}$, the LC filter pass band is $\Delta f_{\text{width}} = 38.4 \text{ Hz}$. While the 38.4 Hz bandwidth combined with a 1.57 kHz peak frequency would, in theory, prevent the 1.64 kHz RC oscillator signal from generating a sufficient Tx signal strength, we found that these components did produce high currents (>2.0 A) in the Tx coil. This may be useful when building a new CSM-EM using substituted parts, because low-cost components with larger uncertainty tolerances still allow the Tx to produce high currents.

### 2.4.3 Receiver Design

The CSM-EM Rx antenna coil (Figure 2.4a) has the same dimensions and wire wraps as the Tx antenna, although due to material heterogeneity the Rx coil resistance and inductance differ slightly from those of the Tx coil. The transmitted signal measured by the Rx unit is filtered through an LC circuit that can be easily refitted to enable the Rx unit to pass different frequencies. The Rx coil has an intrinsic inductance $L_{\text{coil}} = 12.7 \text{ mH}$, a resistance $R_{\text{coil}} = 2.7 \text{ \Omega}$, connected to a tuneable capacitor $C_{\text{coil}} = 770 \text{ \text{nF}}$ (Figure 2.4b). The resulting LC filter has a peak frequency of $f_{\text{coil}} = 1.61 \text{ kHz}$ and a pass-band width of
\[ \Delta f_{width} = 33.8 \text{ Hz} \] due to the finite resistance of the Rx coil.

The filtered Rx signal (modeled in Figure 2.2a) is amplified using an inverting amplifier configuration powered by two 9 V batteries (see equation 2.4). Figure 2.4b illustrates the amplifier setup with a gain \( G = 100 \), set by \( R = R_1 \) and \( R_f = R_F \). \( R_F \) is a variable resistor that allows the Rx gain to be changed without hardware refits. The op-amp gain increases the signal amplitude, allowing the user to observe minute signal changes on a readable scale. The gain value was chosen because it shifts the Rx input signal up by two orders of magnitude, making any changes in the secondary field more easily observable on a 0.1 mV resolution multimeter (shown in Figure 2.2b). The filtered and amplified signals are measured as an RMS voltage by a DMM connected across the amplifier output.

2.4.4 Construction and Cost Considerations

Table 2.1 presents the itemized cost for all instrument components. The only tools and resources required for the build are a soldering iron, wire strippers, electrical tape and zip ties for structural integrity, and containers for electrical modules. The basic components used in the device build allow the user to substitute most components for those available, which has the potential to significantly lower the build cost. In most situations, the largest cost contributor - wire - can be re-purposed from other sources. While the OPA549 power amplifier unit can be built from scratch (Figure 2.3b), prefabricated boards provide greater Tx system durability, improve the modularity of design, and facilitate refit and repair.

2.5 Validation

The CSM-EM design goals specify that the system can function at frequencies and Tx-Rx offsets similar to those found in commercially available FDEM instruments. We used the Geonics EM-34 commercial Tx for validation and comparison. The CSM-EM system set to function at 1.67 kHz because of its size and compatibility with the Tx frequencies available on the EM-34.
Figure 2.4 (a) Low-cost CSM-EM Rx system. The Rx coil (with attached tuning capacitor $C_{coil}$) acts as a LC bandpass filter for a given frequency. The signal is passed through an inverting amplifier and an RMS voltage is measured by a DMM. (b) Low-cost CSM-EM Rx circuit diagram consisting of the Rx coil/tuning capacitor, an OPA741 inverting amplifier powered by two 9 V batteries, and a DMM.
Table 2.1 Cost breakdown (in USD) for parts required to construct and operate the system. Note that this estimate assumes all products are bought new. Many components (especially wire) can be repurposed, allowing the system to be built at a lower overall cost.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (USD) / Unit</th>
<th># of Units</th>
<th>Cost (USD) / Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Gauge Wire</td>
<td>0.38 / m</td>
<td>400 m</td>
<td>152.00</td>
</tr>
<tr>
<td>Coil Frame</td>
<td>12.49</td>
<td>2</td>
<td>24.98</td>
</tr>
<tr>
<td>Breadboard, Wires, Banana Plugs</td>
<td>12.50</td>
<td>1</td>
<td>12.50</td>
</tr>
<tr>
<td>9 V Batteries</td>
<td>2.28</td>
<td>2</td>
<td>4.56</td>
</tr>
<tr>
<td>12 V Motorcycle Batteries</td>
<td>29.67</td>
<td>2</td>
<td>59.34</td>
</tr>
<tr>
<td>Switches</td>
<td>1.20</td>
<td>1</td>
<td>1.20</td>
</tr>
<tr>
<td>Electrical Components</td>
<td>4.97</td>
<td>1</td>
<td>4.97</td>
</tr>
<tr>
<td>741 Op-amp module</td>
<td>1.69</td>
<td>2</td>
<td>3.38</td>
</tr>
<tr>
<td>549 Power amp Module</td>
<td>40.00</td>
<td>1</td>
<td>40.00</td>
</tr>
<tr>
<td>Multimeters</td>
<td>29.97</td>
<td>2</td>
<td>59.94</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>362.87</strong></td>
</tr>
</tbody>
</table>

We ensured device functionality through laboratory tests designed to observe whether the CSM-EM could: (1) function at the desired frequencies; (2) emit stable Tx signals at amplitudes comparable to (or even greater than) the EM-34 Tx; and (3) detect conductive objects in a free-air environment at reasonable Tx-Rx offsets. After successfully validating functionality in the laboratory environment, the CSM-EM instrument has been tested in an outdoor setting by performing a survey over an area containing a known conductive anomaly.

### 2.5.1 Laboratory Validation Tests

The first laboratory trial tested whether the CSM-EM Rx could detect a clear sinusoidal signal at a given frequency with a visible change in the signal amplitude when a conductor was placed nearby. For the trial, the Rx unit was placed in a near free-air environment (i.e., elevated on a mobile stand in the laboratory) at 10 m offset from the CSM-EM Tx. The Tx and Rx were set to function at 1.6 kHz. The brown curve in Figure 2.5 shows an oscilloscope display of the CSM-EM Rx signal with and without introducing a piece of sheet metal near the Rx. The Rx signal shown is a total field measurement; a superposition of the primary Tx field and secondary fields generated from nearby conductive materials. As shown on the oscilloscope display, the Rx signal had a frequency of 1.67 kHz, with an
RMS voltage of 271.9 mV, and a peak-to-peak (Pk-Pk) amplitude of 880.0 mV without the sheet metal present (yellow curve). After the conductive body was placed between the CSM-EM Tx and the CSM-EM Rx, the signal amplitude decreased to less than half of the previous amplitude (brown curve). This is because the secondary field created by conductive bodies destructively interferes with the primary signal, attenuating the total field measured by Rx. The RMS voltage was well within the resolution of a standard DMM. The initial test demonstrated that the Rx measured a stable field very close to the expected Tx frequency with an amplitude of several hundred mV, which is sufficiently observable on commercial DMMs. The test also indicates that the Rx responds to the destructive interference of secondary fields from the conductor, and that the amplitude change can be measured by a DMM as an RMS voltage.

Figure 2.5 CSM-EM Rx signal measured on an oscilloscope using a Rx gain of $G = 100$ at a 10 m Tx-Rx offset with (yellow curve) and without (brown curve) introducing a piece of sheet metal near the Rx antenna. The signal with the sheet metal present is less than half the amplitude of that without metal present. The CSM-EM Tx generated the signal for both measurements.
Next, we tested the CSM-EM Tx unit for its ability to produce a stable signal of comparable strength to that of the EM-34 Tx unit. The system was set up in the same orientation as the former laboratory trial, but using a Rx gain of $G = 50$ at a 5 m Tx-Rx offset. The signal frequency in this trial was, as expected, nearly identical to the measured Rx signal from the previous trial (1.67 kHz). The RMS voltage was 3.42 V and the Pk-Pk amplitude was 9.9 V using the CSM-EM Tx and decreased to less than half the original amplitude when using the EM-34 Tx (yellow and brown curves in Figure 2.6, respectively), demonstrating that the CSM-EM Tx can produce a stable signal of comparable strength to that of the EM-34 Tx.

Figure 2.6 Low-cost CSM Rx signal (attached to oscilloscope) using an amplifier gain $G = 50$ at a 5 m Tx-Rx offset with the EM34 Tx (brown) and low-cost CSM-EM Tx (yellow). The amplitude of the signal received from the CSM-EM Tx is over twice that of the EM34 Tx.
2.5.2 Field Validation Tests

Field validation testing involved completing an outdoor field survey over a shallow metallic conductor to test system sensitivity to a conductive object, and a qualitative Tx-Rx offset test. The field survey target was a manhole cover located at the surface in the outdoor Colorado School of Mines Geophysical Discovery Laboratory (GDL). The GDL is a flat sod-covered area with a thin layer of soil 0.5 m deep covering the surface. Backfill underneath the soil continues to a depth of 2.0 m, with thick shale units extending deeper into the subsurface [49]. While the GDL can be considered geologically homogeneous for near-surface FDEM surveying applications, there is a large amount of electrical and plumbing infrastructure running throughout the area.

The survey consisted of two primary transects: (1) an east-west test line over the manhole cover, and (2) a parallel control line 4.0 m to the north of the test line (Figure 2.7a). The first trial used the EM-34 Tx with the CSM-EM Rx on the test line. The second trial combined the CSM-EM Tx and Rx units again on the test line. Finally, a third trial used the combined CSM-EM Tx-Rx system but on the control line for calibration purposes. All Tx and Rx units were set to function at 1.6 kHz. The CSM-EM system for all trials was oriented along the two survey lines shown in Figure 2.7a with the Tx and Rx units separated by a fixed 5.0 m offset and starting at 25.0 m and 30.0 m easting, respectively. Measurements proceeded westward every 0.5 m and stopped when the Tx unit reached the 0.0 m easting coordinate. The CSM-EM Tx current and Rx RMS voltage were measured at each survey location. The current measurements ensured that the CSM-EM Tx unit exhibited a stable current output throughout the survey. Figure 2.7b presents RMS voltages measured by the CSM-EM Rx and shows a significant anomaly detected in both the EM-34 Tx and CSM-EM Tx trials (blue and orange curves, respectively) when either the Tx or the Rx passed directly over the target. In comparison, the CSM-EM control line data (green curve) exhibited no significant voltage drop. Figure 2.7c shows the current in the CSM-EM Tx over the manhole cover line (blue curve)
and over the control line (green curve).

Figure 2.7 Geometry and results from the CSM-GDL field validation test using a 1.6 kHz Tx frequency. (a) Survey geometry showing the 0.75 m diameter manhole cover surface target located at 18.5 m easting on the test line. The control line is parallel to and 4 m North of the test line. The only other known nearby conductive body is a sprinkler box located close to the survey area. (b) The orange and blue curves show the test line data for the EM-34 Tx and CSM-EM Rx and the CSM-EM Tx and Rx combinations, respectively. Both curves show significant RMS voltage reductions when either the Tx or Rx passes over the target. The green curve presents the control line data unaffected by the surface metal objects. (c) The blue and green curves show CSM-EM Tx current for the test and control lines, respectively. Along the test line, the Tx current dips when the antenna is directly over the manhole cover, as well as at 6.5-7.0 m easting.

The Tx-Rx offset testing was conducted in the GDL area away from the manhole cover, so that measurements could be made over a homogeneous subsurface. The CSM-EM Rx output was observed using an oscilloscope to gauge signal stability and a DMM to measure RMS voltage. Both the Tx and Rx devices were set to the same system parameters from the manhole cover field test. The CSM-EM Tx and the EM-34 Tx were tested separately,
with the CSM-EM Rx in an HCP coupled orientation. Measurements took place at 5.0 m intervals. The EM-34 Tx paired with the CSM-EM Rx was tested starting at a Tx-Rx offset of 10.0 m, and continuing until the sinusoidal Rx signal was no longer resolvable on the oscilloscope. At 10.0 m the EM-34 Tx generated a clean signal with an RMS voltage of 150 mV, representing total field strength. When the system was moved to a 15.0 m offset, the Rx signal was very weak and had an RMS voltage of less than 60 mV. Because the CSM-EM Tx generated a larger signal in laboratory testing compared to the EM-34 Tx, the CSM-EM Tx coupled with the CSM-EM Rx was tested at larger offsets. At 20.0 m, the CSM-EM Tx generated a clean signal with a 130 mV RMS voltage, comparable to the EM-34 Tx signal at 10.0 m offset. At 25.0 m the CSM-EM Tx signal was still resolvable from the background noise, but the RMS voltage had dropped to 80 mV. At 30.0 m offset, the CSM-EM Tx signal was very weak, with an RMS voltage of 60 mV. The offset test demonstrated that the CSM-EM Tx can produce a resolvable Rx signal at up to 25.0 m offset from the CSM-EM Rx unit.

2.6 Discussion

The CSM-EM system provided a variety of results from the engineering design process and the prototype validation tests. We initially designed the CSM-EM unit to be a tilt-angle EM system prototype [50]; however, early laboratory tests suggested that the Tx-Rx system was capable of conducting amplitude-based FDEM measurements when connected to a DMM measuring RMS voltage. While the laboratory and field test results present a proof of concept that the CSM-EM unit is capable of acquiring field-scale FDEM data, they also highlight several challenges experienced during CSM-EM data acquisition and analysis as well as opportunities for further research.

2.6.1 Proof-of-Concept Instrumentation

The CSM-EM unit can function at multiple frequencies at field-scale Tx-Rx offsets in an outdoor environment with a Tx signal strength comparable to that of the EM-34 Tx.
The low-cost components required to construct the system are easily procurable; many parts also could be substituted to further decrease costs. The CSM-EM system is easy to adapt to a wide range of Tx-Rx frequencies with minor hardware changes, and can acquire data using a voltmeter. The system measurements can be connected to the analog-to-digital converter available on most microcontrollers (e.g., an Arduino UNO) for cost-effective and lightweight digital recording.

Field testing demonstrated that the complete CSM-EM system is sensitive to conductive objects and can produce similar amplitude-based data as the EM-34 Tx and CSM-EM Rx combination. The CSM-EM field trials show that the CSM-EM Tx produces larger Rx voltages and more prevalent anomalies than the commercial Tx. The CSM-EM Tx-Rx data have a variance of 0.118 \( V^2 \) over the test line, excluding data points over the target, and a variance of 0.029 \( V^2 \) over the control line. The data for the EM-34 Tx with the CSM-EM Rx have a variance of 0.011 \( V^2 \) over the test line, excluding data points over the target. The higher variance of the data measured using the CSM-EM Tx is significant enough to prevent the system from detecting small-scale near-surface resistivity changes, such as those from geology or fluid content. The CSM-EM Tx current (Figure 2.7c) exhibits similar trends to the CSM-EM Rx voltage when the Tx is directly over the manhole cover. The Tx current signal showed a variance of 0.012 \( A^2 \) over the control line and 0.036 \( A^2 \) over the test line. Along with higher data variance using the combined CSM-EM Tx/Rx, limited sampling of DMM readings make any kind of noise analyses difficult.

Noise present in the CSM-EM field data indicates a lack of stability in the Rx signal and Tx current, which may be due to numerous factors including the lower build quality and reduced rigidity of the CSM-EM antennas, as well as the precision of the low-cost hardware (e.g., resistors, capacitors, inductors, repurposed wiring) used in the CSM-EM Tx build. The CSM-EM antennas were constructed around plastic liners and easily deform, which can affect the stability of signal transmission and could account for the greater observed variance in the Tx and Rx antennas. (The antennas were held flat in the HCP...
orientation to mitigate these effects during trials.) The quality and tolerances of the hardware used in the CSM-EM Tx unit may have affected signal quality during testing. Issues with the hardware component connections could be mitigated by integrating the components into a printed circuit board.

### 2.6.2 Future Development

The testing performed on the prototype CSM-EM system allows for several future developments. While the CSM-EM system resembles the EM-34 in size and shape, next-generation designs could use the same circuitry on a miniaturized scale to create a system more similar in size to lightweight single-operator EM systems. A miniaturized system would require less material (specifically antenna wire) and could function as a single rigid structure. Along with miniaturization, the Tx and Rx tuning capacitors could be attached to rotary switches, which would permit the frequency range of the device to be changed without any hardware modifications.

Microcontroller inboard analog-to-digital converters are capable of voltage and current measurements when combined with basic electrical components [51]. This would allow for the CSM-EM system to digitally record measurements. Including a microcontroller module (e.g., an Arduino or Raspberry Pi) opens up the possibility of future CSM-EM versions to be operated remotely which, when combined with the system’s potentially lightweight nature, opens up opportunities for multi-Tx-Rx experiments.

By combining a more robust build with rapid autologger sampling, we aim to decrease noise during data acquisition and better analyze more densely recorded data through processing. With an improved system, we can determine whether the CSM-EM design is sensitive to small-scale conductivity variations due to geology or subsurface fluid content. Modifications are underway to perform phase-based measurements for a more direct comparison to commercial instruments. These mechanical and data-collection improvements will dictate future applications of the CSM-EM system in near-surface geophysical investigations.
The primary goals of this study were to design, build and validate a low-cost transmitter-receiver FDEM system for under US$500 that is of comparable size and signal transmission strength to commercial grade systems. The CSM-EM device costs US$363 for the current design when using all new parts, and can detect conductive objects in a field environment using amplitude-based signal measurements. The modular design of the unit allows users to easily replace components and to replace the DMM system with a microcontroller-based autologger. The CSM-EM functions at a variety of frequencies with minimal hardware adjustments and produces a stable signal of comparable strength to commercial systems (e.g., the Geonics EM-34 Tx). This proof-of-concept device provides a foundation for the future development and use of low-cost FDEM systems for near-surface geophysical and other related investigations.
CHAPTER 3
DEVELOPING A LOW-COST INDUCED POLARIZATION AND DIRECT CURRENT RESISTIVITY AUTOLOGGING INSTRUMENT FOR FIELD-SCALE STUDIES

3.1 Introduction

Electrical methods are an important component of near-surface geophysical surveying, especially due to the increasing community interest in applications involving groundwater exploration [11, 13, 20, 25, 52], geotechnical investigations [53, 54], and environmental remediation [15, 55]. The direct current (DC) resistivity method has long been used to constrain geological models and to map subsurface fluid concentrations [36], and has been used for such applications as aquifer location, saltwater infiltration, and groundwater contamination monitoring. Induced polarization (IP) methods have been most commonly used in mineral exploration activities [56]; however, IP has recently experienced notable growth in groundwater exploration. In addition, IP has proven useful in pollutant monitoring studies, both to constrain DC resistivity models and to monitor pollutants (such as disseminated sulfides) to which DC resistivity and other geophysical methods may not be sensitive [46]. Recent developments in node-based electrical techniques also have opened up opportunities for large-scale 3-D time-lapse IP monitoring.

With the recent proliferation of low-cost microcomputers, sensors, and open-source software, many users - entry-level and experts alike - have been able to develop and validate purpose-built geophysical equipment for small-scale research projects. Low-cost systems following this methodology include seismic nodes [27–29] and magnetometers [31–33] among others. There have been a number of low-cost instruments developed to perform DC resistivity measurements, both laboratory-scale autologging systems built for materials testing [26, 40] and field-scale instruments for groundwater exploration [20, 25]. Each of these instruments has demonstrated an ability to acquire data of comparable
quality to commercial-grade systems in the laboratory and in field-scale geophysical investigations, and has the potential for use in time-lapse geophysical monitoring investigations. Beyond time-lapse monitoring, autologging resistivity instruments have the potential to acquire both DC resistivity and time-domain IP data. While low-cost resistivity instruments may lack the durability and many of the safety features of commercial instruments, their low fabrication costs and ability to be tailored to specific environments could allow for numerous devices to be built and deployed in low-cost geophysical networks for single vintage and/or time-lapse monitoring applications.

Induced polarization methods represents a subset of ground resistivity-based geophysical techniques that are sensitive to chargeable characteristics of the subsurface. These are particularly relevant for mineral exploration scenarios involving searching for low-grade orebodies [36] and for pollution monitoring when aiming to discriminate disseminated sulfides and heavy metals in saturated environments [56]. Time-domain IP methods investigate the capacitive characteristics of the ground - known as chargeability - by measuring a voltage decay after a DC resistivity measurement is taken. With an extended measurement time, a hybrid DC/IP instrument effectively can acquire two data sets with the same physical set-up, making a low-cost system capable of simultaneously acquiring DC resistivity and IP data a strong candidate for nodal-based geophysical monitoring.

The goal of this study is to develop and validate a low-cost IP autologging system for under US$300. This proof-of-concept system has the capability of acquiring and storing DC resistivity and time-domain IP data for time-lapse monitoring applications and can function at both laboratory and field-scale electrode offsets. The system design allows it to delineate between changes in the subsurface conductivity and chargeability physical properties. The system is controlled using an Arduino UNO microcontroller, which allows for the manual setting of survey parameters, an LCD-screen display, and a digital recording system.

This chapter starts by describing the theory behind DC resistivity and time-domain IP methods and their uses in near-surface geophysical investigations and environmental
monitoring applications. We then discuss our low-cost instrument design and provide
details on its construction and use. Next, we present desktop validation tests of the
prototype system for measurements acquired with breadboard circuits as well as over a test
tank in a laboratory environment. We conclude by discussing the device’s safety and cost
considerations along with suggestions for future improvement and potential near-surface
geophysical applications.

3.2 Methods

The section provides a brief overview of the theoretical principles and some
methodological considerations behind both of the DC resistivity and IP techniques.
Readers interested in a more complete theoretical treatment are referred to standard
reference texts on these subjects [47, 56, 57].

3.2.1 DC Theory Overview

Direct current (DC) resistivity is a method used to measure ground resistivity by
observing subsurface electrical current flow. It is particularly useful for finding conductive
or resistive bodies that differ from the background fields, as well as for discerning
subsurface fluids from surrounding geologies. As a result, DC resistivity has experienced
significant use in water exploration and in hydrology studies.

DC resistivity surveys are generally conducted by injecting a steady-state electrical
current into the ground through a pair of transmitter (Tx) electrodes A and B and
measuring the voltage distribution on the surface over a pair of receiver (Rx) electrodes M
and N. An analog for a basic DC resistivity setup is an electric circuit (see Figure 3.1a),
where a DC power source capable of injecting current $I$ is attached to a load of resistance
$R$ by the Tx electrodes.

A typical DC resistivity measurement, over a non-chargeable subsurface, consists of
turning on the transmitter current for a finite amount of time and measuring the resulting
voltage potential over the Rx electrodes. After this period, the transmitter current is
turned off, then turned on in the opposite direction for the same period of time, and finally turned off. Ideally, this produces a negative voltage of the same magnitude. This procedure is repeated several times and is used to obtain a mean voltage potential, along with a measurement uncertainty [57]. The Tx current direction is reversed during measurement to avoid the effects of electrode polarization, which could otherwise affect resistivity measurements [57]. While in ideal situations the potential across the Rx is 0 V, most real world environments are effected by spontaneous potential (SP), which causes the measured voltage to be offset by a non-zero value even when the Tx is off. This effect can be remedied by recording a voltage before each resistivity observation and subtracting the resting value from the measured voltages.

Figure 3.1 (a) A simplified expression of DC resistivity measurements using a simple electric circuit. The transmitter system and current measurement is represented by the A and B power source and the ammeter. The receiver module is represented by the voltmeter attached to M and N electrodes. The bulk resistance of the ground is represented by resistor $R_g$. (b) A basic dipole array with the current electrodes A and B on the outside of the array and voltage electrodes M and N at the center of the array. The electrode separation distances $[r_1, r_3, r_2, r_4]$ influence the geometric factor used to calculate apparent resistivity.

The electric potential over the resistive body can be measured as a voltage $\Delta V$ across the Rx electrodes using a device such as a digital multimeter (DMM). The relationship between these values and thus information on subsurface resistivity distributions can be
derived using a 3-D form of Ohm’s Law:

\[ \rho_a = KR = K \frac{\Delta V}{I}. \]  

(3.1)

Due to heterogeneity within the subsurface, measuring bulk resistance alone does not provide meaningful information. Therefore, it is important to quantify data as apparent resistivity \( \rho_a \) distributions within the subsurface. While the theoretical concepts behind DC resistivity are straightforward, reconstructing the exact depths and distributions of ground resistivities is challenging. Therefore, apparent resistivity is used as an approximation of ground resistivity as an input for geophysical inversions. Apparent resistivity is related to the bulk ground resistance \( R \) by the geometric factor \( K \), which is dependent on the orientation of the Tx and Rx electrodes. Using differing electrode separations, equation 3.1 can be expanded to account for the geometry of different four-electrode array configurations (see Figure 3.2b):

\[ \rho_a = \frac{\Delta V}{I} 2\pi \left( \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right). \]  

(3.2)

There are a number of different electrode configurations used for DC resistivity surveys depending on several factors including the target location and depth, survey time constraints, and instrument hardware limitations. These configurations can range from simple geometries meant to acquire 1-D vertical electrical sounding (VES) data to large-scale 3-D setups. The orientations of the Tx and Rx electrodes are typically defined by one of several array geometries (see Figure 3.2), each with its respective geometric factor \( K \).
Figure 3.2 Five commonly used electrode configuration used for DC resistivity acquisition. The geometric factor $K$ is used with the $\Delta V/I$ ratio to calculate apparent ground resistivity.

### 3.2.2 IP Theory Overview

Whereas DC resistivity is used to measure subsurface resistivity distribution, IP methods measures the ability of the ground to build up ionic charges, quantified as chargeability. This effectively introduces a chargeable effect to the simplified circuit Figure 3.4. The chargeability of a material describes its ability to temporarily store energy as a result of variations between the mobility of fluids within a material, as well as variations in ionic and electrical conductivity due to the presence of disseminated metals [57].

While the current injection procedure from DC resistivity measurements remains the same in time-domain IP methods with the associated data acquired simultaneously, the voltage response and subsequent voltage decay measurement differs from DC resistivity measurements alone. When a current is injected into a chargeable subsurface, the measured voltage will experience a sudden initial increase of $V_o$, and then slowly build up until reaching the final measured saturation value $V_m$ (see Figure 3.3) [56]. The voltage measured when the transmitting current is on, $V_{on}$, is dependent on the time current being
transmitted. This effect, while much more complex in subsurface environments, can be approximated by

\[ V_{on}(t) = V_\sigma + V_s[1 - e^{-t/\tau}] \]  

where \( V_s \) is the over-voltage constant and governs the difference between the potential over the ground when the current is turned on at \( t = 0 \) s, \( V_\sigma \), and when the ground reaches charge saturation \( V_m \). Constant \( \tau \) describes the rate at which the subsurface is polarized. When the transmitter current is turned off, the measured voltage drops from \( V_m \) to a value equal to \( V_s \), after which the measured voltage decays over time. This effect can be approximated and modeled in a simplified environment using

\[ V_{off} = V_s[e^{-t/\tau}] \]  

In the time domain, intrinsic chargeability \( \eta \) can be defined as the ratio between the over-voltage \( V_s \) and the voltage measured at saturation \( V_m \),

\[ \eta = \frac{V_s}{V_m}, \]  

where units are dimensionless, and values will fall in the range \( \eta \in [0, 1] \).

While using \( V_s \) is convenient for conceptual understanding and IP signal modeling, it is impractical to measure the voltage at the instant current is shut off due to the large transience behavior introduced by breaking a circuit [48]. The challenge behind this is that the over-voltage must be measured before the signal decays to a point where it becomes irresolvable from noise. For time-domain measurements, the most straightforward method for obtaining chargeability is to sample the voltage decay \( V_{off} \) over a finite period after the current has been cut off. Using these measurements, we can obtain (a discrete version of) the integral of \( V_{off} \) decay and define integrated chargeability \( M \) as the ratio of the integral of the voltage decay \( V_{off} \) over time and the measured voltage \( V_m \):

\[ M = \frac{1}{V_m} \int_{t_1}^{t_2} V_{off}(t) \, dt. \]
Figure 3.3 (a) Current output for both DC and time-domain IP data collection. The current is turned on in the positive direction, cut-off, activated in the reverse direction, and then cut-off again at a set interval. Current reversal prevents electrode polarization. (b) Voltage response from a chargeable subsurface. After the current is activated, the signal will slowly saturate to reach an over-voltage. Once current is cut off, the potential will experience an immediate large drop and then slowly decay. This decay can be measured and integrated to gain a integrated chargeability measurement. (c) Voltage response from nonchargeable subsurface, which is proportional to the current activation and cut-off from the transmitter system.

Unlike the dimensionless intrinsic chargeability, integrated chargeability is most commonly measured in milliseconds (ms). While the range of current transmission on/off times varies, the most commonly employed technique is the Newmont Standard [56], commonly referred to as $M_{311}$, which dictates on and off times of 3.0 s with an integrating interval of 1.0 s for a half-duty cycle. Similar to DC resistivity, multiple cycle measurements are made, both with forward and reverse current directions, to compute a single averaged IP measurement [58].
Similarly to Figure 3.1, the properties of a chargeable subsurface can be approximated using a circuit model (Figure 3.4). Based on the Warburg Impedance model [59, 60], this circuit accounts for the different conduction pore-space pathways within a material (i.e., those areas containing materials such as clay or metallic materials versus purely resistive materials) via the electrode capacitance $C_w$, the intrinsic material resistance $R_{w2}$, the material reaction resistance $R_{w1}$, and the Warburg impedance ($Z_m$).

![Electrode impedance equivalent circuit for a chargeable subsurface](image)

Figure 3.4 Electrode impedance equivalent circuit for a chargeable subsurface [60], where $C_{w1}$ represents electrode capacitance, $R_{w2}$ the material resistance, $R_{w1}$ the reaction resistance of the material, and $Z_w$ the Warburg impedance.

### 3.3 Instrument Design

The CSM DCIP2022 autologging instrument (Figure 3.5) consists of three major modules: the current transmitter, the receiver circuit, and the Arduino-based recording and control module. The instrument can be programmed to take DC and/or IP measurements at a specified interval for time-lapse survey applications or to acquire measurements upon command for active geophysical surveys. When prompted, the control module controls DC current transmission and direction through a series of relays attached to the transmitter module. During transmission, the current input is measured, averaged, and recorded by the system. The receiver unit acts as an autoranging voltmeter controlled by the Arduino unit. During current transmission, the receiver can safely measure values ranging between
±80.0 V with 12-bit precision through a four-layer voltage divider series. When current is cut off, the receiver can switch to a high-gain mode to accurately measure the voltage decay effects. These data are recorded by the control module with corresponding GPS data on an SD card and can be displayed on the instrument LCD screen. The design and functionality of each module are described below, with the corresponding code libraries included in Appendix A. The specifications and tolerances for the hardware components vary within the system depending on its respective purpose; however, all components can be easily modified depending on available parts and the intended application.

Figure 3.5 The entirety of the CSM DCIP2022 system. A 12 V car battery powers a 120 V inverter capable of providing power to the Tx circuit and the Arduino control module. The control module manages the Tx circuit by controlling the relay output pins and measures the resulting voltage through an auto-ranging voltmeter Rx circuit that is based on a multilayered voltage divider design.
3.3.1 Transmitter Design

The Tx module design is based off of the CSM DS2020 low-cost DC system improved with the incorporation of digital recording, Tx signal filtration, and user safety. The design, validation and field functionality of the system are detailed in the work corresponding to the design of the DS2020 system, along with its use in a Geoscientists Without Borders project [20].

Figure 3.6 shows the Tx circuit diagram. The Tx module can be powered using a 120 V or 220 V AC power source depending on regional electrical standards. In the field, it is typical to use a 12 V car battery attached to a power inverter; however, the system can be directly plugged into an outlet, generator, or any other suitable AC source. The DC signal is then passed through a bridge rectifier circuit, which converts it to an equivalent DC signal. A manual safety switch was included in the circuit to ensure that the Tx remains off until the user is ready. This feature was added because current injection is controlled by a relay module rather than by manual on/off switching by the user as with the DS2020 design [20].

The DC signal is passed through using a low-pass resistor and capacitor (RC) filter to protect the inverter from overloading and to smooth any transience from the AC signal conversion and/or from rapid on-off current injection. A low-pass RC filter consists of a resistor connected in series with the circuit and a capacitor connected in parallel with the circuit, as shown in the Tx circuit diagram (Figure 3.6). The DS2020 used a series-based RC circuit to smooth out the high-frequency transience that could endanger the power inverter; however, it did not purposefully filter out noise from the AC power source. A low-pass RC filter allows for better control of the frequencies being passed through the transmitter, which, while not necessary for DC resistivity measurements, becomes an important consideration for time-domain IP measurements. While the electrical impedance of a resistor is not sensitive to signal frequency, the complex impedance of a capacitor, called capacitive reactance, is inversely proportional to the frequency of the signal passing
through it [48]. Using specific resistor $R$ and capacitor $C$ pairings, we can leverage this property to build a filter that will pass signals less than a certain cutoff frequency $f_c$:

$$f_c = \frac{1}{2\pi RC}. \quad (3.7)$$

The primary sources of transience within the Tx signal are extremely high frequencies caused from quick on-off current injection and 50 Hz or 60 Hz signals depending on the specific AC power source used. The resistor $R_1 = 330 \, \Omega$ and capacitor $C_1 = 10 \, \mu F$ used in the Tx create a cutoff frequency $f_c = 48.23 \, \text{Hz}$. These parameters effectively filter out noise from the AC power source and counter-electromotive force.

After the signal is filtered, the current is measured using a shunt resistor $R_s = 5.5 \, \Omega$ connected to analog-to-digital converter (ADC) of the control module. The ADC acts as a 16-bit voltmeter. The shunt resistor has an extremely low resistance compared to the load voltage (primarily the subsurface) and can be used to calculate the current passing through the Tx using a voltage measurement.

The two nodes on the circuit, labeled 1 and 2 in Figure 3.6, are connected to a four-channel relay controlled and powered by the Arduino module. The A and B electrodes are attached to two relay channels, one positive and one negative. This allows the user to effectively control the current direction by selecting which electrode will be defined as positive. This is important for ensuring that electrode polarization does not overwhelm the desired IP signal.
Figure 3.6 The Tx circuit design consisting of a bridge rectifier that turns the AC input into a DC signal. Transience within the signal is filtered out by an RC lowpass filter (R6 and C2). Finally, the signal is injected into the ground through electrodes A and B. The relay module attached to A and B controls the current flow through the ground, allowing the user to reverse current to prevent electrode polarization. The current input signal can be measured as a voltage over the shunt resistor $R_s$.

### 3.3.2 Receiver Design

The Rx module (Figure 3.7) is made up of an RC filter attached to the M and N electrodes and a chain of voltage-divider circuits that function to create an auto-ranging AC voltmeter. The RC filter has the same $R_1$ and $C_1$ values as the Tx module to remove any nearby noise sources. The filter is attached to a series of resistors, acting as a layered voltage divider, connected to optocouplers. A simple voltage divider is a circuit consisting of two resistors $R_1$ and $R_2$ in series, with voltage measured over $R_2$:

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2}.$$  \hspace{1cm} (3.8)

The ratio of the respective impedance values effectively produces an output voltage that is only a fraction of the input voltage. This circuit is important for DC voltage measurements because the Arduino-based voltage equipment can only measure voltages up to 5 V safely, while, many DC responses over resistive media will far exceed this threshold.
While a simple voltage divider can remedy challenges reading large voltages, it would make it impractical for the Arduino to make accurate small (i.e., mV scale) time-domain IP measurements. To accomplish this, the Rx uses a multilayered voltage divider that can be adjusted, using optocouplers, for high- and low-voltage signals. An optocoupler allows a low-voltage circuit, such as the Arduino control module, to control a high-voltage circuit without directly interfacing with it. This is important for user safety and to protect the delicate hardware making up the control module. For this application, the optocouplers act as digital switches controllable by the Arduino digital pins and are by default left open. The series of resistors act as an adjustable voltage divider circuit, allowing the user to control the analog gain of the signal being read by the ADC by activating different optocouplers. One ADC channel (labeled as A1) is set to read the voltage at the N electrode. A0 on the analog-digital converter (ADC) is attached to the series of optocouplers. Depending on which optocoupler switch is closed, the ADC will read a differential voltage (A0-A1) between different resistors, allowing the user to read voltage inputs with different gain factors.

The voltmeter activates with the final optocoupler, between $R_4$ and $R_5$, which gives the voltage divider the smallest gain of 0.025 for signals below 80 V. If the signal is below 8 V, the circuit will be closed and the optocoupler between $R_3$ and $R_4$ is activated, giving the divider a gain of 0.25. If the signal is below 4 V, this will continue to a gain of 0.5 and, finally, a gain of 1 if the signal is below 2 V.

All resistor values used in the voltage divider were calibrated to within 0.1 Ω resistances of the circuit diagram. The ADC chip gain used has a bit resolution of 0.0625 mV. For safety reasons, each voltage measurement is assigned an uncertainty of 0.1 mV.
Figure 3.7 The Rx module consists of a low-pass RC filter to smooth out signal transients. The signal is then passed through a multilayered voltage divider. Optocouplers controlled by the Arduino module act as switches, along voltage to be measured between different resistor combinations, effectively changing the gain of the voltage divider. This protects the ADC chip attached to A0 and A1 in case of large voltages, but allows the chip to maintain accurate measurements when recording small voltage changes.
3.3.3 Data recording

The entirety of current transmission, signal gain, and voltage recording is managed by an Arduino UNO united connected to a ADS1115 16-bit ADC chip. This ADC is capable of recording signals ±4.1 V with a precision of 1 bit = 0.062 mV at a programmable rate ranging from 8 to 860 samples per second. The control module can be powered indirectly by any AC power source such as an inverter or outlet, or by any laptop device interfacing with the Arduino unit. The Arduino unit can carry out its programmed task as long as it is powered; however, a laptop or mobile device connected to the microcontroller is necessary to operate the device and obtain a live data feed.

The code for controlling the DCIP2022 is included in Appendix A. The screen interface allows the user to easily control the on/off times of current transmission and voltage measurement, as well as the data sampling rate and voltage signal gain. Tailoring these parameters to different survey conditions can be useful when experiencing large changes in the average subsurface resistivity and electrode spacing. The serial monitor shows a live feed displaying “Transmitter Current (mA), Receiver Voltage (mV), and the Measurement Time Stamp (ms)”. The activation and cutoff of Tx current is signified by readings showing both the transmitter current and receiver voltage at exactly 0.0 mA or 0.0 mV, respectively. This is because in most near-surface environments there will be at least a small spontaneous potential voltage effect from the earth, ensuring that the voltage measurement will not be exactly 0.0 mV when the Tx is off. In the case that this affects data readings, the dummy values of “0, 0, timestamp” can be easily changed in the code.

The ADC chip (Figure 3.3) and four-channel relay are both powered using the 5 V outlet and one of the GND pins on the Arduino UNO. While the ADC chip communicates with the Arduino through the SCL and SDA pins, the relay is controlled by digital pins D6 through D9 on the Arduino UNO.
Figure 3.8 Illustration of the Arduino microcontroller, which manages the Tx current injection and Rx gain. A USB input to the Arduino allows the user to set survey parameters and manually control each measurement made by the DCIP2022 system.

### 3.3.4 Construction and Cost Considerations

Table 3.1 presents the itemized cost for all instrument components. The only construction tools necessary are wire-strippers, electrical tape, and a screwdriver (for screw-down pins on the relay). The basic electrical components making up the device can be substituted to alter the corner frequency of the low-pass RC filters and the gain levels on the multi-layer voltage divider. Along with basic electrical components, any opto-transistor-type optocoupler can be used in the Rx build. Similar to the original
DS2020 DC resistivity meter [20], the main contributor to the cost of the DCIP2022 system is the power inverter. The device can function on most 120 V or 220 V AC power sources, meaning that the power inverter potentially can be excluded if a generator or outlet is available.

Table 3.1 Approximate cost breakdown (in USD) for parts required to construct and operate the system. Wires, electrodes, and battery power source are not included due to being required components for all DC/IP systems. Materials such as wires and general-purpose resistors may be priced lower than suggested above.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (USD) / Unit</th>
<th># of Units</th>
<th>Cost (USD) / Item</th>
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<tbody>
<tr>
<td>Arduino UNO</td>
<td>19.00</td>
<td>1</td>
<td>19.00</td>
</tr>
<tr>
<td>4-Channel Relay Breakout Module</td>
<td>8.00</td>
<td>1</td>
<td>8.00</td>
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<tr>
<td>ADS1115 Breakout Chip</td>
<td>5.50</td>
<td>1</td>
<td>5.50</td>
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<tr>
<td>PC817C Optocoupler</td>
<td>0.50</td>
<td>4</td>
<td>2.00</td>
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<tr>
<td>Bridge Rectifier</td>
<td>3.00</td>
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<td>Power Cable</td>
<td>3.00</td>
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<td>3.00</td>
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<tr>
<td>SPST Switch</td>
<td>1.00</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>Miscellaneous Connectors</td>
<td>5.00</td>
<td>1</td>
<td>5.00</td>
</tr>
<tr>
<td>330 Ω 10W Resistor</td>
<td>6.00</td>
<td>2</td>
<td>12.00</td>
</tr>
<tr>
<td>10 Film Capacitor</td>
<td>4.50</td>
<td>1</td>
<td>9.00</td>
</tr>
<tr>
<td>Various Resistors (Ω-2kΩ)</td>
<td></td>
<td></td>
<td>5.00</td>
</tr>
<tr>
<td>Spare Wire</td>
<td></td>
<td></td>
<td>5.00</td>
</tr>
<tr>
<td>Power Inverter (500 W minimum)</td>
<td>85.00</td>
<td>1</td>
<td>85.00</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>152.50</strong></td>
</tr>
</tbody>
</table>
3.4 Circuit Validation Tests

The DCIP2022 system was tested on a simplified circuit model to determine if the autologging module was sensitive enough to detect voltage decay changes due to chargeability changes. While the simple RC circuit used in the trials is not a precise circuit model of a chargeable subsurface (as in Figure 3.4), it successfully approximates changes in a measured voltage response due to chargeability. For testing purposes, the DCIP2022 system was attached to a series circuit of three 1.0 kΩ resistors (Figure 3.9) in a Wenner array electrode orientation. The DCIP2022 transmitter unit was powered using a 10 V constant voltage DC power source. To add a capacitive effect to the system, capacitors of different values were attached in parallel to the center resistor over electrodes M and N. Each trial consisted of a single measurement, gradually increasing the capacitance of the circuit from 0 µF to 50 µF.

Figure 3.9 (a) Close-up of circuit set-up with a single capacitor attached in parallel with the center resistor. (b) Testing set-up showing the DCIP2022 attached to the circuit, and the 10V DC power source used for current injection.

Figure 3.10 shows the voltage decay curve results of the different trials. When testing over the 0 µF circuit, the voltage decayed to near-zero values within 0.10 s of positive current shut-off and 0.15 s of negative current shut-off. The 1 µF test showed similar trends to the 0 µF test. As the circuit capacitance was increased to 20 µF, 30 µF, and 50 µF,
though, the voltage decay time also increased for voltages after the positive and negative current shut-off times, observations which are consistent with the expected circuit behavior.

Figure 3.10 (a) Voltage decay curve 0.1 s after the positive current injection is shut off to avoid the transient behavior. As the capacitance of the circuit increases from 0 $\mu$F to 50 $\mu$F, the area under the voltage decay curve increases. (b) Voltage decay curve 0.1 seconds after the negative current injection is shut off. A similar trend to (a) can be observed as capacitance increases from 0 $\mu$F to 50 $\mu$F.

3.5 Chargeable Body Validation Tests

The primary benchmarking test performed using the DCIP2022 system was its ability to sense the presence of a chargeable object in an artificial subsurface environment, approximated by a glass tank filled with playground sand (Figure 3.11a). The electrode geometry was set up as a Wenner array using 0.2 m electrode-spacing. Each electrode was buried 4 cm in the sand environment and treated with a half liter of salinated water to ensure robust electrode coupling. The DCIP2022 prototype was powered using a 700 W, 120 V power inverter attached to a 12 V car battery.
Figure 3.11 (a) An 100 cm long, 45 cm wide, 45 cm deep glass tank is filled with playground sand. The electrodes are set in a Wenner array configuration at 20 cm spacing, buried 4 cm deep. The pyrite body when added to the sand tank was buried in the center (highlighted in blue) directly between M and N at a depth of 10 cm. (b) The iron pyrite was used as an anomalous chargeable body with rough dimensions of 10 cm long, 5 cm wide, and 5 cm high.

Once the DCIP2022 system was set up, four individual measurements were taken over the sand tank. Each measurement consisted of a single duty cycle with an on-off current time of 3.0 s, following the Newmont IP standard [61]. The first measurement (shown in Figure 3.12) only recorded the current transmission from the system. This was due to extremely high voltages unique to the sand tank environment that will be expanded upon in the discussion. The current signal had an average variance of 0.49 mA$^2$ when current was injected and 1.43 mA$^2$ when not injecting current.

After taking the initial current measurement, three full-duty cycle measurements were acquired in the sandbox (Figure 3.13a). The on-cycles had an average variance of 0.56 V$^2$ during positive current injection and 159.33 V$^2$ for negative current injection. The off-cycle variance was 0.18 V$^2$. Next, a sample of iron pyrite (Figure 3.11b), a chargeable sulfide mineral, was buried at a depth of 10 cm centered between the M and N electrodes.
Four full duty-cycle measurements were acquired with the pyrite present (Figure 3.13b). The on-cycles had an average variance of 0.12 V\(^2\) during positive current injection and 81.58 V\(^2\) for negative current injection. The off-cycle variance was 0.025 V\(^2\).

All information pertaining to subsurface chargeability is contained within the voltage decay curves recorded between 6.0-9.0 s and 12.0-15.0 s along the duty cycle (Figure 3.14). This information contains a strong signal from the counter-electromotive force when current is cut-off. First, the SP constant is subtracted from the voltage decay. Using equation 3.6 the integrals for each decay curve were calculated over a time-period starting at 0.1 s after current-cutoff, and ending at 3.0 s after cutoff. Next, the integral values were normalized by the measured voltage to gain a integrated chargeability measurement (see Table 3.2). The reported chargeability data for each half-duty cycle were averaged after being calculated.
Figure 3.13 (a) Three cycles of data acquired from a single duty-cycle measurement over the sand tank without any pyrite. (b) Four cycles of data from a single duty-cycle measurement over the sand tank with buried pyrite.

Finally, the differences between the calculated chargeability with pyrite present $M_{pyrite}$ and without pyrite $M$ were calculated for the half-duty cycles across all measurements.

Figure 3.14 A zoom-in showing the decay curves (a) after the positive current cut-off (cycle time 6.0-9.0 s) and (b) after the negative current cut-off (cycle time 12.0-15.0 s). The typical decay curve shape cannot be visually observed due to the large effects of the counter-electromotive force from current cut-off.
Table 3.2 Calculated integrated chargeability for each half-duty cycle, as well as the differences between the calculated average chargeability with and without the pyrite body present for the positive half-duty cycle (6.1-9.0 s) and the negative half-duty cycles (12.1-15.0 s). Measurement uncertainty 0.1 mV for the receiver, and is detailed in the Receiver Design.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>M (6.1-9.0 s) [ms]</th>
<th>M (12.1-15.0 s) [ms]</th>
<th>Pyrite Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.309</td>
<td>1.187</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>2.508</td>
<td>1.024</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>2.710</td>
<td>0.893</td>
<td>No</td>
</tr>
<tr>
<td>Average M</td>
<td>2.509</td>
<td>1.035</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>5.894</td>
<td>2.089</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>6.457</td>
<td>1.869</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>6.497</td>
<td>1.763</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>6.567</td>
<td>1.735</td>
<td>Yes</td>
</tr>
<tr>
<td>Average (M_{pyrite})</td>
<td>6.354</td>
<td>1.864</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\[
M_{pyrite} - M (6.1-9.0 \text{ s}) = 3.85 \text{ ms} \\
M_{pyrite} - M (12.1-15.0 \text{ s}) = 0.83 \text{ ms}
\]

3.6 Discussion

The DCIP2022 system provided results useful for device hardware design and for future field-testing applications. While laboratory testing results illustrate the capabilities of the instrument, they also show a variety of remaining challenges stemming from the instrument design and laboratory testing environment. Future field-testing and design goals for the DCIP2022 are based on the instrument’s performance at a laboratory scale.

3.6.1 Proof-of-Concept

The DCIP2022 can detect approximate chargeability changes in modeled circuits due to a capacitive object and can inject a steady current into a laboratory-scale sand tank environment and record a resolvable voltage signal. As the capacitance of the modeled circuit increased, the decay curves recorded after positive and negative current injection became larger and more gradual, showing that the sensor modules are sufficiently sensitive to detect small scale changes in voltage decay. By averaging multiple calculated integrated
chargeability measurements and comparing them, the presence of a chargeable anomaly in the sand tank is detectable by the DCIP2022 system in a resistive laboratory-scale environment. The system can be controlled and data saved using any laptop or mobile device connected to the DCIP2022 by a USB cable.

Laboratory testing demonstrated that the DCIP2022 system is likely sensitive to highly chargeable anomalous objects, and that it can produce and record a relatively steady current signal in small-scale environments. While the variance of the current transmission signal appeared to be high when both transmitting and after current cut off, Figure 3.12 illustrates that this is due to uncommon, large deviations from the average current detected by the DCIP2022 system, and that the overall current signal is relatively stable. The voltage signals for trials with and without pyrite included in the sand tank environment showed low variance when current was cutoff and when current was being transmitted in a positive direction. The only high variance in the signal appeared to occur when current was being transmitted in a negative direction. Negative current transmission also appears to correspond with much larger magnitude voltages (averaging at -60 V with and -110 V without pyrite present) compared to the voltages detected during positive current transmission (averaging close to 16 V with and 40 V without pyrite present).

The voltage decay after current cut-off was heavily subdued by the effects of counter-electromotive force due to current-cutoff. Although the low-pass RC filter installed in the system did not appear to fully wipe out the effects of this, the large transience that is typically present after current cutoff was smoothed by the filter. Information pertaining to the chargeability was only able to obtained by examine the difference between the chargeability integrals of each voltage curve. The calculated chargeabilities are consistent for both half-duty cycle measurements with and without pyrite present. While the magnitude of the chargeabilities calculated for the first half-duty cycle are greater than in the second, both cycle results show that the calculated chargeability with pyrite present are higher than the calculated chargeabilities without pyrite present.
Aside from the chargeability results, the noise present in both current and voltage signals points to issues with the DCIP2022 handling high-voltage signals, effectively shorting out the ADC chip. This issue stems from two major factors: (1) the minimalist hardware nature of the DCIP2022 system that is much less electronically durable than any commercial system; and (2) the extremely resistive nature and unique geometry of the sand-tank environment. While the system is not designed to measure voltages larger than 80 V, previous studies using the same transmitter setup show that the voltage across the M-N electrodes in most field environments rarely exceeds 2 V. This may indicate that the system will perform better in less resistive environments and at field-scale electrode offsets.

3.6.2 Future Development

Future directions for the DCIP2022 consist of continued instrument testing using a variety of subsurface materials, testing the device in outdoor environments, and hardware improvements to bolster the safety and durability of the machine. While the sand tank represents one environment that the DCIP2022 could face, it is constrained by its small size and high resistivity. Calibrating the DCIP2022 in the lab with more conductive, subsurface material will be helpful to acquire additional benchmark data to more fully determine the capability of the device to conduct IP measurements. This benchmark testing will also help to determine whether the current and voltage measuring challenge experienced in the sand tank tests is specific to that environment or whether it is a more general hardware problem. While the basis of the IP design was tested at field offset up to 90 m electrode spacing using a Wenner array, the autologger has yet to be tested at large offsets. Testing the functionality of the device at field-scale offsets will determine its maximum depth of investigation. Along with geophysical data acquisition, field testing will provide a gauge of the device durability and ease of use. This will directly affect the housing design and functionality of future DCIP2022 prototypes.

While the current DCIP2022 is controlled through a laptop or mobile device, ideally the system could be controlled through a simple LCD screen GUI and limited keypad input.
This would make it much more efficient when deploying the device for time-lapse monitoring projects. The DCIP2022 Arduino module also has the potential to include GPS, Bluetooth, and cellular connectivity through low-cost breakout board add-ons. This would allow the IP system to be specifically tailored for small-scale active surveys, time-lapse monitoring, and even remotely controlled nodal-based investigations.

Along with more robust field-testing and improved control module hardware, the electronic durability and safety of the device could also be improved with a variety of simple electrical components. This may include components like fuses to prevent harmful currents, diode clamps across voltage inputs, and redundant circuits to ensure continued functionality during long device deployments. While the functional part of the DCIP2022 is circuitry, the device housing can be tailored to whichever environment the instrument is deployed. This opens up the opportunity for potential users to invest more in instrument durability for longer-term surveys in harsh environments, or to retain a simple, stripped-down design for small-scale research projects.

### 3.7 Conclusions

The primary goals of this study were to design, build and validate a low-cost time-domain IP auto-logging system for under US$300. The DCIP2022 costs US$153 to fabricate, can record steady current and voltage signals at high sampling rates, and is sensitive to chargeable objects at the laboratory-scale. The device is easy to control and acquire data with a laptop or mobile device attached with a USB cable, and can be reprogrammed with specific survey parameters by the user. This proof-of-concept device forms the basis for future developments to low-cost DC/IP systems and, with low-cost hardware add-ons to the control module, such future devices potentially could be used in 2-D reconnaissance surveys, time-lapse IP monitoring, and/or future 3-D nodal investigations.
Although environmental, geotechnical, and resource issues pose ever-pressing humanitarian challenges to low and middle-income countries, low-cost and purpose-built geophysical equipment can be leveraged to collect valuable information needed to address such issues without purchasing expensive commercial hardware and services or engaging in invasive and expensive drilling and excavation activities. Electrical and electromagnetic methods are particularly strong candidates for developing low-cost instrumentation due to the ease of data acquisition and processing and their wide applicability to environmental and geotechnical challenges that most often more significantly affect low-income communities.

The primary goals of the frequency-domain electromagnetics (FDEM) study were to build and validate a low-cost transmitter receiver system for under US$400 that is of comparable size and signal transmission strength to commercial-grade systems. The current CSM-EM FDEM instrument prototype costs US$363 and can function at multiple frequencies. The system produces a stable signal of comparable strength to commercial systems and can detect near-surface conductive objects at the transmitter and receiver units using off-the-shelf digital multimeters (DMMs) for measurements. This prototype device provides a foundation for continued development and use of low-cost FDEM systems for near-surface geophysical and other related investigations.

The primary goals of the induced polarization (IP) study were to build a low-cost prototype time-domain IP autologging system for under US$300 by combining current low-cost direct current (DC) resistivity meter designs with low-cost microcomputers and sensors and to validate the system’s ability to delineate between a non-chargeable subsurface and a subsurface with a chargeable anomaly present. The DCIP2022 system
costs US$153 is capable of autologging current and voltage data separately in highly resistive laboratory sandbox settings. The microcontroller allows the user to control the direction and time window of current transmission, along with the data recording windows. The device demonstrated its ability to sense the presence of a highly chargeable anomalous object in a sand tank environment. The prototype DCIP2022 builds a platform for future low-cost IP and DC autologging systems, specifically for monitoring highly chargeable anomalies in near-surface geological settings.

4.1 Future Work

Future work on the CSM-EM FDEM system will focus on improving the mechanical stability and robustness of the device and implementing the same circuitry in a miniaturized FDEM design similar in size to single-operator EM systems. Along with stability modifications, the next generation CSM-EM device will have adjustable frequencies through manual switches, which will allow the functioning frequency to be adjusted without hardware modifications. The DMM recording systems can be replaced with a microcontroller module capable of Rx voltage and Tx current measurements, which would give the CSM-EM autologging capability and allow for remote data collection and multi-Tx-Rx experiments. The breadboard-based circuit can also be replaced by a printed circuit board to help increase hardware stability and improve system safety. Additional safety features, such redundant stopper circuits and directional power connectors will be added for ease-of-use. An autologging capability and improved mechanical stability would improve the system’s signal-to-noise ratio during data collection. Spatially dense data sampling could allow the system to detect small-scale changes due to geology or subsurface fluid content, which are below the signal-to-noise resolution of the current CSM-EM model.

Future improvements to the DCIP2022 system will primarily consist of testing at field-scale offsets similar to those used with the DC resistivity system on which the Tx component of the DCIP2022 is based. These trials will be used to validate the system’s ability to function at large electrode offsets, possibly up to 90 m, and to detect subsurface...
changes in resistivity and chargeability. The autologging ability of the system will be tested in time-lapse trials at laboratory and field scales, flooding a permeable area with a conductive fluid, and taking periodic measurements as the fluid dissipates over time. The future DCIP2022 prototype will have improved electronic durability to ensure that microcontroller electronics are isolated from high transmitter voltages even in highly resistive environments, such as a laboratory-scale sand bed. Along with improving electronic durability, the DCIP2022 will be interfaced with GPS and data storage units, allowing the device to record data for prolonged amounts of time without being connected to a laptop or mobile device. Future iterations of the DCIP2020 may include remote communication, allowing for the deployment of nodal areas for environmental time-lapse monitoring. This proof-of-concept device provides a foundation for future testing and development, along with the potential for active electrical surveying and remotely controlled time-lapse surveying.
REFERENCES


APPENDIX
IP2022 SYSTEM ARDUINO CODE

#include <Adafruit_ADS1X15.h>

Adafruit_ADS1115 ads; /* Use this for the 16-bit version */

double Gain=0;
float multiplier = 0.0625F;
float R_s = 5.5;
int on_off_time = 3000;
int sampling = 0;

int CH2 = 2;
int CH3 = 3;
int CH4 = 4;
int CH5 = 5;

int PosA = 6;
int PosB = 7;
int NegB = 8;
int NegA = 9;

void setup() {
    // put your setup code here, to run once:
    Serial.begin(9600);
pinMode(PosA, OUTPUT);
pinMode(PosB, OUTPUT);
pinMode(NegB, OUTPUT);
pinMode(NegA, OUTPUT);
pinMode(CH2, OUTPUT);
pinMode(CH3, OUTPUT);
pinMode(CH4, OUTPUT);
pinMode(CH5, OUTPUT);

digitalWrite(PosA, HIGH);
digitalWrite(PosB, HIGH);
digitalWrite(NegA, HIGH);
digitalWrite(NegB, HIGH);

//ads.setGain(GAIN_TWOTHIRDS); // 2/3x gain +/- 6.144V 0.1875mV (default)
//ads.setGain(GAIN_ONE);       // 1x gain  +/- 4.096V 0.125mV
ads.setGain(GAIN_TWO);        // 2x gain  +/- 2.048V 0.0625mV

if (!ads.begin()) {
    Serial.println("Failed to initialize ADS.");
    while (1);
}

void loop() {
if(Serial.available() == true){
    char input = Serial.read();
    if(input == 'p') {
        V_I_read(multiplier, R_s, on_off_time, sampling);

        I_on_P();

        V_I_read(multiplier, R_s, on_off_time, sampling);

        I_off();

        V_I_read(multiplier, R_s, on_off_time, sampling);

        I_on_N();

        V_I_read(multiplier, -1*R_s, on_off_time, sampling);

        I_off();

        V_I_read(multiplier, R_s, on_off_time, sampling);

        Serial.println("0, 0, 0");
    }
}
}
/***********************************************************************
Functions
***********************************************************************

void V_0025_gain() {
    digitalWrite(CH2, HIGH);
    digitalWrite(CH3, LOW);
    digitalWrite(CH4, LOW);
    digitalWrite(CH5, LOW);
}

void V_025_gain() {
    digitalWrite(CH2, LOW);
    digitalWrite(CH3, HIGH);
    digitalWrite(CH4, LOW);
    digitalWrite(CH5, LOW);
}

void V_05_gain() {
    digitalWrite(CH2, LOW);
    digitalWrite(CH3, LOW);
    digitalWrite(CH4, HIGH);
    digitalWrite(CH5, LOW);
}

void V_1_gain() {
    digitalWrite(CH2, LOW);
    digitalWrite(CH3, LOW);
}
digitalWrite(CH4, LOW);
digitalWrite(CH5, HIGH);
}

// Reads voltage w/ proper gain
double V_read(double gain) {
    int16_t results;
    double multADC = 0.0625F;
    results = ads.readADC_Differential_0_1();
    return results * multADC / gain;
}

void I_off()
{
    // Current Off
    digitalWrite(PosA, HIGH);
    digitalWrite(PosB, HIGH);
    digitalWrite(NegA, HIGH);
    digitalWrite(NegB, HIGH);
}

void I_on_P()
{
    // Current On (Positive Polarity)
    digitalWrite(PosA, LOW);
    digitalWrite(NegB, LOW);
}

void I_on_N()
{ // Current Off (Negative Polarity)
  digitalWrite(NegA, LOW);
  digitalWrite(PosB, LOW);
}

//Sets gain value on signal (controls optocoupler gates)
double V_set_gain() { //Sets Gain

  V_0025_gain();
  double gain = 0.025;

  if (abs(V_read(0.025)) < 16000)
    {
      V_025_gain();
      gain = 0.25;

      if (abs(V_read(0.25)) < 8000)
        {
          V_05_gain();
          gain = 0.5;

          if (abs(V_read(0.5)) < 4000)
            {
              V_1_gain();
              gain = 1;
            }
        }
    }
}
return gain;

}

void V_I_read(float ADC_mult, float R_shunt, int16_t t, int16_t sample)
{
    unsigned long tic = millis();

    while(true) {
        unsigned long toc = millis();
        if(toc - tic > t - 1)
        {
            Serial.print("0, 0, ");Serial.println(toc);
            break;
        }

        int16_t Ires = ads.readADC_Differential_2_3();
        double g = V_set_gain();
        int16_t Vres = ads.readADC_Differential_0_1();
        Serial.print(Ires * ADC_mult/R_shunt);
        Serial.print(",");
        Serial.print(Vres *ADC_mult / g);
        Serial.print(",");
        Serial.println(toc);
        delay(sample);
    }
}

}