2007

SPATIAL LOCATION OF ELECTROSTATIC DISCHARGE EVENTS WITHIN INFORMATION TECHNOLOGY EQUIPMENT

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In this thesis, a system to locate an electrostatic discharge (ESD) event within an electronic device has been developed. ESD can cause a device to fail legally required radiated emissions limits as well as disrupt intended operation. The system used a fast oscilloscope with four channels, each channel attached to a high frequency near-field antenna. These antennas were placed at known locations in three dimensional space to measure the fields radiated from the ESD event. A Time-Difference-of-Arrival technique was used to calculate the location of the ESD event. Quick determination of the ESD event location provides developers with a tool that saves them time and money by eliminating the time-consuming and tedious method of general ESD mitigation within a product.

KEYWORDS: Electromagnetic Compatibility (EMC), Electrostatic Discharge (ESD), Time Difference of Arrival (TDoA), Spatial Location, FCC
SPATIAL LOCATION OF ELECTROSTATIC DISCHARGE EVENTS WITHIN
INFORMATION TECHNOLOGY EQUIPMENT

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December 4th, 2007
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THESIS

Robert A. Oglesbee

The Graduate School
University of Kentucky
2007
SPATIAL LOCATION OF ELECTROSTATIC DISCHARGE EVENTS WITHIN
INFORMATION TECHNOLOGY EQUIPMENT

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Electrical Engineering at the University of Kentucky

By

Robert A. Oglesbee

Lexington, Kentucky

Director: Dr. William T. Smith, Professor of Electrical Engineering

Lexington, Kentucky

2007

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Chapter 1. Introduction

1.1 Introduction to EMC and Radio Frequency Emissions Testing

Electromagnetic Compatibility (EMC) refers to the ability of electronic equipment to operate in a common environment with other electronic equipment without causing or suffering unacceptable loss of function. Some aspects of EMC are dictated by governmental bodies such as the Federal Communications Commission (FCC) in the United States, and the International Special committee on Radio Interference (Comite International Special Des Perturbations Radioelectriques, CISPR) in Europe. Most countries in the world use derivatives of either the FCC or CISPR rules for determining the acceptable EMC performance of products allowed on the market. The philosophy of the FCC regarding EMC is to limit radio frequency emissions, but to allow manufacturers to monitor their own immunity performance. CISPR prefers to govern all aspects of EMC.

The FCC and CISPR rely in part upon standards committees (and their own internal committees) to generate test methods and criteria. One of the most important standards committees for EMC is the Accredited Standards Committee on Electromagnetic Compatibility, C63, which is accredited by the American National Standards Institute (ANSI) and is part of the Institute of Electrical and Electronic Engineers (IEEE).
1.2 Impulsive Noise and Radiated Emissions Testing

The topic of this paper is most relevant to the radio frequency emission aspect of the FCC and CISPR rules, and in particular the limits and measurement methods for radio frequency emissions above 1GHz. The FCC Part 15 regulations lay out the rules for measuring the emissions of electronic devices. There are three frequency ranges for most devices: conducted emissions (noise measured on the AC mains) from 150kHz to 30MHz, radiated emissions (noise measured with an E-field antenna) from 30MHz to 1GHz, and radiated emissions from 1GHz to as high as 40GHz.

Radiated emissions testing in the higher frequency range is not always required, and is determined by the characteristics of the electronic device under test. For printers which are unintentional radiators (no internal active radio transmitters), and most other Information Technology Equipment (ITE), the highest frequency range tested is determined by the following table from pages 21-22 of the FCC part 15 rules. In Europe, CISPR has similar requirements for the measurement frequency range. Many ITE products today fall into the category requiring measurement up to 2GHz or 5GHz.
Table 1.1: Highest Frequency of Measurement for ITE Unintentional Radiators [1]

<table>
<thead>
<tr>
<th>Highest frequency generated or used in the device or on which the device operates or tunes (MHz)</th>
<th>Upper frequency of measurement range (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 1.705</td>
<td>30</td>
</tr>
<tr>
<td>1.705 – 108</td>
<td>1000</td>
</tr>
<tr>
<td>108 – 500</td>
<td>2000</td>
</tr>
<tr>
<td>500 – 1000</td>
<td>5000</td>
</tr>
<tr>
<td>Above 1000</td>
<td>5th harmonic of the highest frequency or 40 GHz, whichever is lower</td>
</tr>
</tbody>
</table>

For radiated emissions testing, four basic things are needed: an Open Area Test Site (OATS) or semi-anechoic chamber, an antenna, RF cables, and an appropriate radio frequency receiver. The differences between the radiated emissions frequency ranges of above or below 1GHz (other than the actual frequencies) are the antennas and detection methods used. Both ranges use antennas appropriate for the application: biconical, log-periodic dipole array (LPDA), or bi-log (hybrid biconical and LPDA) [37] for the lower range, and horn antennas for the higher range. The detection method for the lower range is the Quasi-Peak detector, whereas the higher range uses both a Peak and an Average detector [35].

The peak detection method for the higher frequency range is central to this paper. Both Quasi-Peak and Average detection have inherent filtering (relatively slow rise and fall times in the detector), whereby low-repetition impulsive noise is suppressed in the reading. However, a Peak detector registers the full amplitude of impulsive noise. This can be problematic for electronic devices that generate such impulsive noise.
1.3 Necessity for Location and Mitigation of Impulsive Noise

As operating frequencies continue to increase, more electronic devices and equipment require testing above 1GHz. If the detection methods were the same for radiated emissions testing both below and above 1GHz, electronics manufacturers would only have the normal known difficulties of passing the FCC and CISPR limits. However, the change from Quasi-Peak detection to Peak detection means that impulsive noise that was once filtered out in all but the worst cases becomes an issue.

There are two main types of impulsive noise, electrical or charge induced. Electrical noise consists of things such as data bursts, asynchronous clocks, and anything else to do with digital circuits. Charge induced impulsive noise is due to sparks, or inductive arcs, of electricity and is usually referred to as static electricity. Static electricity can be generated wherever dissimilar materials rub together (tribo-electric) or other sources of large charge differences are present. Tribo-electric impulsive noise typically causes more problems because the spark that is generated has a very fast rise-time and high amplitude. Since electrical noise is much lower in amplitude, it doesn't usually cause a problem unless major mistakes have been made in the design of the device.

Electronic devices that incorporate moving parts, such as printers, are particularly good at creating static electricity. This is because printers move paper through many rollers, have many gears and motors, and in the case of laser printers, have large static voltage potentials present on different materials. All of these are opportunities for a
high enough voltage potential to develop and a static discharge to occur. In fact, CISPR realized this and in their new requirements for high frequency testing, they excluded static electricity from the peak measurement limits:

_The peak detector limits shall not be applied to disturbances produced by arcs or sparks that are high voltage breakdown events. Such disturbances arise when ITE devices contain or control mechanical switches that control current in inductors, or when ITE devices contain or control subsystems that create static electricity (such as paper handling devices). The average limits apply to disturbances from arcs or sparks, and both peak and average limits will apply to other disturbances from such ITE devices._ [3]

Unfortunately, the FCC has not seen fit to include the same relaxation in the limits. This makes the location and mitigation of impulsive noise, such as electrostatic discharges, an important part of the electromagnetic compliance process. In particular, developing an easy-to-use laboratory setup for locating product-generated ESD will help increase productivity in the compliance lab and save time and money invested in the development of ITE products.

### 1.4 Description of Electrostatic Discharge Locator System

In this thesis, a system to locate an electrostatic discharge event has been developed. The system used a fast oscilloscope with four channels, each channel attached to a high frequency near-field antenna. All four antennas were of similar construction.
These antennas are placed at known locations in three dimensional space, usually around an ITE product, such as a printer.

When a discharge occurs within the measurement space, the four near-field antennas pick up the resultant electromagnetic fields. When the waveforms are displayed on the oscilloscope, a time difference of arrival (TDoA) measurement is made to determine when the electromagnetic fields arrived at each antenna. Since the locations of the antennas are known and the TDoA’s are known, a technique called Hyperbolic Positioning [4] is used to solve for the location of the ESD event. A software program was also developed to interface with the oscilloscope, and to calculate and display the ESD event location.

The remainder of this thesis is organized as follows. Chapter 2 presents background on electrostatic discharge (ESD), the consequences of ESD, and how it is measured. Details on several methods for detecting ESD are discussed along with previous studies on the topic. Chapter 3 deals with the selection of antennas for measuring ESD within a product. Common E-field and H-field antennas, both commercially available and homemade, are studied for their ability to detect ESD. Chapter 4 delves deeper into the antenna selected for detecting ESD by examining the construction and other features. A brief Method of Moments (MoM) modeling is performed. Chapter 5 details the creation and study of a program to interact with an oscilloscope, measure the ESD pulse with four antennas, and calculate a probable location for the ESD.
event. Chapter 6 identifies further work, alternate uses of the antenna system, and presents the thesis conclusions.
2.1 Characteristics of Electrostatic Discharges

Electrostatic discharge (ESD) occurs in many places and takes on several different forms. The type of ESD that most people recognize occurs in low humidity when they rub their feet across thick carpet and touch something metal, such as a doorknob or light switch plate. International immunity standards such as IEC 61000-4-2 [5] help protect information technology equipment (ITE) from this, and other, types of ESD by subjecting products to a controlled ESD source and requiring a certain level of performance. This helps prevent externally induced problems with a product, but does not address internally generated ESD events. These internal events can not only cause products to malfunction, but can also cause a product to fail legal limits on radiated emissions. Before addressing this last point, it is important to know how ESD is generated and its general waveform characteristics.

The above example of rubbing socks along carpet to build up a charge, is a form of tribo-electric charging. Tribo-electric charging happens when two different materials rub together, where at least one of which is an insulator [6]. When the materials are separated, the surface of one of the materials will strip electrons from the other. The amount of charge transfer is dependent on the material type, surface properties (conductivity and lubricity), and mechanical properties (contact pressure and speed of separation). A version of the tribo-electric series is reproduced below. Materials near the top left become positively charged and become less so with ascending number as
you travel down the chart. Materials that are widely separated on the chart in number tend to transfer more charge.

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>air</td>
<td>12</td>
<td>paper</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>human skin</td>
<td>13</td>
<td>cotton</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>asbestos</td>
<td>14</td>
<td>steel</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>fur (rabbit)</td>
<td>15</td>
<td>wood</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>glass</td>
<td>16</td>
<td>sealing wax</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>mica</td>
<td>17</td>
<td>hard rubber</td>
<td>28</td>
</tr>
<tr>
<td>7</td>
<td>human hair</td>
<td>18</td>
<td>nickel, copper</td>
<td>29</td>
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<td>wool</td>
<td>20</td>
<td>gold, platinum</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>silk</td>
<td>21</td>
<td>acetate fiber (rayon)</td>
<td>32</td>
</tr>
<tr>
<td>11</td>
<td>aluminum</td>
<td>22</td>
<td>polyester (mylar)</td>
<td>33</td>
</tr>
</tbody>
</table>

A second method of charging is called induction [6]. With induction, a nearby charged surface induces a polarization of a nearby conductive body. A discharge event then occurs unless there is another discharge path. When combined, the total charge is still neutral, but the charge is mobile on one surface and immobile on the other. The charged conductor then can discharge to another conductor or other oppositely charged surface. One example of this on an electronics production floor is when charge is generated on the insulating material of a component package. Charge is then induced on the component leads attached to the internal circuitry. Once the leads touch a grounded surface, an ESD event occurs [7].

Another method of charging is called capacitive charging. Using the $Q = CV$ equation, if the charge remains constant but the capacitance decreases due to movement, then voltage can dramatically increase and cause a discharge.
All three types can occur in a product such as a printer. Tribo-electric charging and inductive charging can be generated by ungrounded rollers or shafts within the product, either as a result of a shaft rotating within a plastic ring, or as charged paper passes over plastic pieces. Capacitive charging can result due to the printing process where high voltages are generated to transfer toner from one component to another.

In many cases, humidity has an impact on how high a voltage can be generated. High humidity tends to lessen the severity of ESD. Table 2.2 shows the different voltage levels generated at different humidity levels. This dependency can impact radiated emissions testing of any product that tends to produce static discharges. Testing in low humidity may make a product fail legal radiated emissions limits, whereas testing in high humidity may result in no problems.

<table>
<thead>
<tr>
<th>Activity</th>
<th>20% Relative Humidity</th>
<th>80% Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking across vinyl floor</td>
<td>12kV</td>
<td>250V</td>
</tr>
<tr>
<td>Walking across synthetic carpet</td>
<td>35kV</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Arising from foam cushion</td>
<td>18kV</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Picking up polyethylene bag</td>
<td>20kV</td>
<td>600V</td>
</tr>
<tr>
<td>Sliding styrene box on carpet</td>
<td>18kV</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Removing Mylar tape from PC board</td>
<td>12kV</td>
<td>1.5kV</td>
</tr>
<tr>
<td>Shrinkable film on PC board</td>
<td>16kV</td>
<td>3kV</td>
</tr>
<tr>
<td>Triggering vacuum solder remover</td>
<td>8kV</td>
<td>1kV</td>
</tr>
<tr>
<td>Aerosol circuit freeze spray</td>
<td>15kV</td>
<td>5kV</td>
</tr>
</tbody>
</table>

A related ESD-like event called Partial Discharge (PD) has also been the subject of much study, particularly in how to locate it [8, 9, 10, 11]. Partial Discharge is a problematic source of ESD in high voltage applications. It is one of the forms of
ESD that is not due to incidental charging, but is generated by the beginning of high voltage insulation breakdown (not yet fully shorted). This occurs in buried transmission lines, stator windings, columns of high voltage insulating disks, and other high voltage applications.

No matter the source of the ESD event, the characteristics of the arc itself and its radiated emissions tend to have many similar characteristics. Knowing these characteristics will help identify an event as being due to ESD, and not some other event. ESD events tend to be single events, as opposed to repetitive events generated by other noise sources [12]. This is because it may take quite some time for conditions to be right for another discharge in the same location. However, the more moving parts a product has, the more likely it is that ESD will happen with regularity.

An important characteristic of an ESD event is the frequency content of the arc. If the frequency content is too low, it will be very difficult to locate the source since the pulse would be fairly wide in the time domain. If the frequency content is too high, then it may be difficult to even detect the pulse. Based on experience testing products, it is known that emissions from static discharge events are measured above 1GHz. One paper on the damages due to ESD stated two general conclusions: “1. EMI level for electronic equipment is not always in proportion to the discharge voltage,” and “2. Physical movement induced ESD tends to have high frequency content and high energy.” [12].
Several other papers have indicated defined frequency ranges for common ESD spectral content. One paper states that when ESD occurs, the discharge time is usually 10 nanoseconds or less, with a resulting broadband frequency spectrum from 10MHz up to 2GHz [7]. Another found that, depending on voltage level, relative humidity, speed of approach, and the shape of the charged object, the upper frequency limit could easily exceed 1GHz, and may reach as high as 5GHz [18].

Another paper [13] observed a spectrum bandwidth greater than 1.8 GHz. Since this paper was investigating the characteristics of ESD pulses, several other important observations were made. The author (M. Honda) found that the interference potential to other electronics was proportional to the acceleration component of the electromagnetic energy, not the charged energy in the metal object. It stands to reason, if the interference potential mentioned in this paper is high, then the same characteristics would produce high radiated emissions. The author named the acceleration quantity “WARP” for working amplitude rate of change product since its dimensions were Joules/sec²/m². These units were derived from his equation for WARP [13]:

\[
WARP = VA \frac{di}{dt}
\]  

(2.1)

where \( V \)=discharge voltage, \( A \)=effective cross section factor of the receptor, and \( di/dt \)=time rate of change of the discharge current. He also suggested that the time
derivative of the Poynting vector $P = E \times H$, $dP/dt$, controlled the EMI effect radiated fields [27].

M. Honda found that indirect ESD tended to have a more severe impact on computer equipment than direct ESD, most likely because of high radiated fields. He created indirect ESD by sliding a charged metal chair into another metal chair (to simulate an office environment), and then created a more reproducible setup with a charged electrode jig. His general observations included, in addition to the high bandwidth, that the radiated spectrum continued to increase until about 8kV, and that around 9kV the spectrum bandwidth began to diminish. Although he also found that these results were highly dependent on the specific characteristics of the discharge geometry. One other important observation was that the ESD waveform started out impulsive and then became oscillatory.

This author, M. Honda, continued his investigations into ESD in further papers [14]. Expanding on his concept of the acceleration component, WARP, he found that low voltages had the largest acceleration component, and therefore had the highest radiated fields. As the discharge voltage increased, the current rise time increased as well. He found that 7kV to 9kV events had electromagnetic fields that traveled the farthest. His explanation for this was that at higher voltages energy was more easily converted to heat and less energy was converted to electromagnetic fields.
Another paper [15] found similar relationships between the field intensity and the discharge voltage. Their measurements indicated that the electromagnetic fields were greater than 150V/m at a 1.5 meter distance from the discharge for short periods of time (a few nanoseconds). In particular, low-voltage events (less than 6kV) had these characteristics. The authors (Wilson and Ma) also noted that the ESD events typically had a large initial spike of energy coupled with fast rise-times. Their experimental results were measured with a broadband TEM horn antenna. They determined that the radiated fields were mostly due to the initial spike of energy. Part of the reason for the spike happening at lower voltages was asserted to be due to the fact that faster approaches (of the discharger) created faster rise-times, and that high voltages required even faster approaches to achieve a fast event.

After studying the ESD event, Wilson and Ma attempted to model the discharge as an electrically short, time-dependent, linear dipole source (z-directed) situated above an infinite perfect electrical conductor (PEC). To model a discharge at the surface of an object, they pushed z' to 0 (the interface with the PEC). Their derivation of the fields (see equation 2.1) suggested that the near-field zone ($1/R^2$ term) was dominated by the amplitude of the current, but that the far-field ($1/R$ term) was dominated by the rate of change of the current (similar to Honda’s WARP concept). After validating their model, they predicted that near-field (10cm away) the predicted electric field exceeded 4000V/m for a 4kV discharge! [15]
\[
\begin{align*}
\vec{E}(\rho, t) & \approx \hat{\rho} \int \frac{\eta_o \rho}{2\pi R^2} \left[ \frac{3i(u)}{R^2} + \frac{1}{cR} \frac{\partial i(u)}{\partial \rho} \right] + \hat{\phi} \int \frac{\eta_o}{2\pi R} \left[ \frac{3z^2}{R^2} + 1 \right] \frac{i(u)}{R^2} + \left[ \frac{z^2}{R^2} + 1 \right] \frac{1}{cR} \frac{\partial i(u)}{\partial \phi} \right] \\
\vec{H}(\rho, t) & \approx \frac{\partial}{\partial \rho} \int \frac{\eta_o \rho}{2\pi R} \left[ \frac{i(u)}{R^2} + \frac{1}{cR} \frac{\partial i(u)}{\partial \rho} \right]
\end{align*}
\] (2.2)

In the above equations, \( R \) is the distance from the discharge point to the observation point \((\rho, \phi, z)\), \( \eta_o \) is the free-space wave impedance, \( c \) is the propagation speed, and \( i(u) \) is the time-dependent ESD current waveform evaluated at time \( u \), where \( u = t - R/c \) [15]. For further derivation details, see the appendix in [15].

A significant component in determining the frequency bandwidth of the ESD event is the rise time of the waveform. Typically, as rise time decreases the upper bound of the significant frequency content increases. In a paper by Kawamata, Minegishi, Haga, and Sato, the authors used a well controlled gap discharge system to measure rise times for both positive and negative discharges at low (<1500V) voltages. At +400V, the discharge rise time was 100 picoseconds and increased in fairly linear fashion to 300 picoseconds for +1300V. For negative polarity, the rise time went from 120 picoseconds to 450 picoseconds [16]. In the case of ESD, rise time typically refers to the first edge of the pulse, regardless of polarity. These rise times would put the upper frequency bound on the order of 2.5GHz.

This was also borne out in an FDTD ESD modeling in another paper [17] where fast rise times generated frequency components above 1GHz. This paper also showed an important aspect of the ESD radiated fields, in that the electric field was higher than the magnetic field.
In summary, ESD events create higher electric fields than magnetic fields. They also have fast rise times in an initial waveform spike which leads to high frequency content in the gigahertz range. In the near field high fields can result, with intermediate voltage levels creating the highest fields.

### 2.2 Consequences of ESD: Erroneous Operation of Equipment

“An ESD seminar participant told how his company's computer system was crashing repeatedly, but, mysteriously, only during the evening work shift. Then someone noticed the crashes coincided with cleanings of the computer room. The culprit was ESD, which was sometimes generated when the vacuum cleaner bumped into the computer system cabinet.” [18]

Electrostatic discharge events can influence electronics from both operational and regulatory aspects. Even though the above example highlights one possible effect of ESD external to electronics, similar things can happen when a product produces its own ESD. Printers, especially early in the development cycle, have been known to reset themselves when pulling paper from optional paper trays, or when pulling paper out of an output bin.

ESD can interrupt normal operation through both direct ESD current damage and indirectly through the fields generated by the discharge event. In addition to immediate damage, ESD will sometimes create latent damage by weakening
electronic components. High impedance voltage sensitive circuitry is susceptible to the electric fields generated by the discharge event. The magnetic fields from the event can couple into low impedance circuitry such as current loops on circuit boards [19].

Potential damage can occur to semiconductor IC’s, photo-masks, magneto-resistive read heads in disk drives, and drive circuits for flat panel displays. ESD problems become worse as devices get smaller, faster, and denser [7]. Exacerbating the issue is that low power electronics are more sensitive to disruption, and that most electronics are now made of plastic instead of metal which makes it harder to shield the circuitry from the effects of ESD [14].

Surprisingly, indirect ESD tends to have a more severe affect on computer equipment than direct ESD [13]. It is one of the strongest sources of reversible or permanent damage in modern electronic equipment. Even when the equipment is well shielded (preventing direct ESD) and suppression devices are included on the printed circuit boards to protect against ESD currents induced on the cables, the strong electromagnetic field from the fast transient ESD current can produce interference. This interference to the internal circuits comes in the form of induced voltages comparable to the signals used in the electronics. Also, because of the high bandwidth of the ESD pulse, resonances can be excited within the electronics which cause further susceptibility problems [20].
2.3 Consequences of ESD: Failure of Legal Radiated Emissions Limits

Even though the operational issues caused by ESD can be severe, the regulatory aspect of internally generated ESD can be equally problematic. In fact, the genesis for this thesis was the radiated emissions failure of a printer during development due to internally generated ESD. In order to fully appreciate how this can happen, a background on radiated emissions testing is necessary.

Radiated emissions measurement of information technology equipment is required by most governments, with the measurement equipment setup, procedures, and techniques specified by [1], [2], [3], [21], [22], and [23], among others. As discussed in the introduction, only the frequency range from 1GHz to 40GHz is relevant to this thesis. This is because of the detector types used by the radio frequency receiver to measure the radiated emissions.

The three detector types used for testing ITE are the peak detector, the quasi-peak detector, and the average detector as defined in [21], [22], and [23]. The peak detector measures and records the maximum reading at the receiver input port during the measurement period. The quasi-peak detector effectively puts a filter in the signal path such that it has a relatively fast rise time response (1 millisecond), but a slow fall time response (550 milliseconds). Additionally, before the resulting value is displayed, it has an output filter with a time constant of 100 milliseconds (this is called the critically damped meter response). This results in a detector that essentially filters out non-repeating instantaneous noise sources, such as ESD. Only constant, or
rapidly repeating, signals will measure near the peak detector value for the same measurement period. Therefore, even very quickly recurring ESD events within a product may not fail the radiated emissions limits where a quasi-peak detector is used. The final detector used in the radiated emissions range is the average detector. This detector simply measures the time-averaged amplitude of the signal at the receiver input port. Like the quasi-peak detector, it will tend to filter out any emissions from sources like ESD.

For products that must measure radiated emissions above 1GHz, a peak detector and average detector measurement is specified. Therefore the full amplitude of an ESD event will be measured due to the lack of filtering in the peak detector. The average detector should not register any significant amplitude from an ESD event.

In addition to a radio frequency receiver that meets the CISPR and ANSI requirements, a radiated emissions measurement must have the following equipment: (1) an antenna for the appropriate frequency range, (2) an approved measurement site such as an Open-Area Test Site (OATS), or some type of absorber-lined chamber, (3) a remotely controlled EUT turntable and antenna positioner, (4) and coaxial cables to attach the receiver to the antenna [22]. Figure 2.1 shows the test setup for an OATS.
The turntable shown in Figure 2.1 holds a nonconductive table upon which the equipment under test (EUT) sets. The turntable rotates 360 degrees so that all faces of an EUT can be measured by the antenna and receiver. In addition, the antenna must be scanned from one meter to four meters above the ground plane. Both horizontal and vertical polarizations of the antenna with respect to the ground plane must be measured. Figures 2.2a-c shows the possible EUT configurations from CISPR 22 [2] [3]. These are similar to those shown in ANSI C63.4 [22].
Figure 2.2a: Tabletop Radiated Emissions EUT Test Setup [2]

Figure 2.2b: Floor-standing Radiated Emissions EUT Test Setup [2]
Recall from Table 1.1 that a product with an internally generated frequency above 108 MHz must measure radiated emissions above 1GHz. Due to the proliferation of high-speed USB, virtually any product with a USB port must then measure above 1GHz. This is because the clock generator for high-speed USB runs at 480MHz.

The radiated emissions limits that an ITE product must meet change based upon frequency, detector method, and geography. Table 2.3 shows these different limits. The FCC limits apply in the United States of America. The CISPR limits apply primarily in the European Union, but most countries around the world have emulated the EU. The FCC limits are specified in uV/m, but in Table 2.3 they have been converted to dBuV/m so that the units are the same for ease of comparison. Since an ESD event will be fully detected by a peak detector, the limits above 1 GHz are of
particular import to this thesis. However, a clause in the CISPR rules [3] specifically excludes static discharge-like events from the peak limits.

<table>
<thead>
<tr>
<th>Table 2.3: FCC and CISPR Radiated Emissions Limits [1] [2] [3]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FCC Class B (3m Meas. Distance)</strong></td>
</tr>
<tr>
<td>Ave. Limit</td>
</tr>
<tr>
<td>30 - 88 MHz</td>
</tr>
<tr>
<td>88 - 216 MHz</td>
</tr>
<tr>
<td>216 - 960 MHz</td>
</tr>
<tr>
<td>960 - 1000 MHz</td>
</tr>
<tr>
<td>Above 1000 MHz</td>
</tr>
<tr>
<td><strong>CISPR Class B (10m Meas. Distance)</strong></td>
</tr>
<tr>
<td>Ave. Limit</td>
</tr>
<tr>
<td>30 - 230 MHz</td>
</tr>
<tr>
<td>230 - 1000 MHz</td>
</tr>
<tr>
<td><strong>CISPR Class B (3m Meas. Distance)</strong></td>
</tr>
<tr>
<td>Ave. Limit</td>
</tr>
<tr>
<td>1 - 3 GHz</td>
</tr>
<tr>
<td>3 - 6 GHz</td>
</tr>
</tbody>
</table>

The possible consequences of failing radiated emissions are the following: increased cost, schedule impact, fines, and in extreme cases, product recall. EMC certification (the process by which a product is tested to applicable RF emissions and immunity standards) can be either be an after-thought on one extreme, or an integral part of the design process on the other extreme. Even when EMC is part of the design from the beginning of a product cycle, failures of the certification tests may only be uncovered
during the final certification testing. In either case, increased cost results from having to change the product at the last minute in order to pass the test suite. Specifically for radiated emissions testing, changes to the product usually include adding toroids, shielding, or printed circuit board (PCB) redesigns. Not surprisingly, these same changes can also impact the scheduled delivery of the product to the market. This is due to having to source the new parts, waiting for new PCB designs, or other subsystem redesigns.

The potentially more severe cases involving fines and product recall can occur when a product is already on the market and is found to fail the legal requirements. This failure of the legal limits can happen either through an oversight during certification testing, a manufacturing change, willful neglect, or any number of other mistakes. Depending on the due diligence of the manufacturer in originally identifying the failure and fixing it, the relevant authority can levy a fine against the manufacturer. In rare cases of willful negligence, and depending on the severity of the failure, a government may force a removal of the product from the market.

In all of these cases, a quick identification of the failure is essential to minimizing the consequences of a legal failure of radiated emissions. At the end of a product cycle often a day-for-day slip in product shipments exists, waiting for a solution to be found.
2.4 Methods for Detecting Electrostatic Discharge Events

ESD has been an issue for many years, especially in manufacturing. It has only been recently that ESD has begun to be a problem for radiated emissions. Therefore, most of the methods for detecting ESD have focused on detecting when an ESD event occurs instead of where it occurs. This was so the discharge source could be correlated to some process or external event, with actual location being a secondary concern.

There are a few ways to detect a potential ESD event before it happens. This usually involves detecting the static charge itself before it has a chance to discharge. This can be done with Coulombmeters with Faraday cups, electrostatic field meters, and electrostatic voltmeters. Only the Coulombmeter with a Faraday cup actually measures charge directly. Other detectors locate charges indirectly by detecting electrostatic fields [7]. These methods are mostly only useful for detecting the possibility for discharge, and therefore of little value for finding an actual discharge. This is especially true in a machine with many moving parts.

One of the ways in which ESD events are detected is to use the effects of the discharge itself as an indicator. Since ESD causes damage in certain circuits, such as the oxide gate in a MOSFET, arrays of these devices can be placed where ESD is suspected. Then, these devices are inspected for damage on a regular basis [7].

Another interesting way to use this aspect of detection was presented by Jacksen, Tan, and Boehm [24]. These authors developed a “Magneto Optical Static Event
Detector”. In order to detect ESD during manufacturing, the authors used the Faraday Effect principal (which is responsible for rotating the polarization of a light beam when it passes through a magneto-optic thin film). An ESD event was then amplified by a FET to change the state of the film. The resulting rotation was observable with a polarizing microscope. Since the detectors are not truly damaged in the detection process, they are slightly more useful on an ongoing basis.

Another way to detect a discharge event is to visually detect the spark. The authors Bendjamin, Gomes, and Cooray presented a paper [25] in which they measured the peak visual radiation from an ESD event and correlated that to magnetic field measurements. They found that the peak optical output matched well with both the measured peak current and the current calculated from the magnetic field. Their purpose was to use the technique to measure the peak current during a discharge between two insulators, but their detectors could also be used to locate discharges within an ITE product. Unfortunately, line-of-sight would be required. In an effort to find the source of an ESD event in a failing product, Lexmark EMC lab engineers have on occasion attempted to visually locate ESD by inspecting a product in darkness. This technique resulted in mixed success.

A method similar to visual detection of an ESD discharge is to detect the discharge using acoustic means. This method has been successfully used in locating insulation breakdowns in columns of high voltage insulators (partial discharge form of ESD) [27]. In this case the technique was to use an acoustic/ultrasound waveguide with
amplifiers. A single microphone was attached to this setup. The amplitude of the ESD discharge sound waves was used as a rough ‘getting hotter’, ‘getting colder’ method. As the amplitude increased, the investigators assumed they were getting closer to the discharges. This method would also be severely limited in a product with moving parts that would add to background noise.

The most used method for detecting an electrostatic discharge involves the electromagnetic fields generated by the discharge. The simplest method for detecting the EM fields is an AM radio tuned to static [7]. Anyone that has listened to AM radio during a thunderstorm could intuitively realize this. Similar to the acoustic method, an AM radio can be set next to a suspected source of ESD. As radio gets closer to the source, the amplitude of the static bursts heard over the radio speakers gets louder. Unfortunately, the spatial resolution of this technique is not very good, and is really limited to finding a faulty piece of equipment on a factory floor, clean room, or server farm.

The next step up from an AM radio is to use an antenna in combination with a threshold detection circuit. Several authors have explored this possibility and successfully used it to detect ESD. The paper that referenced the AM radio technique also listed several commercially available threshold detectors available at the time [7]. The Lucent Model T100 used a small loop antenna attached to an instrument and a counter. This allowed for the measurement of the number of times a certain piece of equipment experienced a discharge event. The Sanki Model ES81V used a short
monopole antenna. The slightly more complicated Credence Technologies EM Eye CTM041 used direction antennas to find the ESD through both proximity and the direction of maximum signal strength. Mostly these commercial testers were more useful in showing that a discharge occurred, but not where it was located. Especially since they could be deceived by equipment panels and grounded metal components, reflectors and absorbers, as well as other radio frequency sources.

Along similar lines as the commercial detectors, Greason et. al. [19] developed an ESD monitor that used both E- and H-field sensors, a detector section with programmable thresholds, a central processing unit to control the system, and a serial optical communication to a remote system for monitoring. They made this detector battery powered and with optical communication in order to isolate it from both the system under observation and the monitoring system. Their device had a small signal bandwidth of 1GHz and used a short monopole and a small half-loop as the antennas. A precursor to their work was shown in one of Honda’s previous papers, where he used a 2.5 centimeter antenna with 5mV and 120mV detection levels at the antenna output [14]. Honda was able to measure 5mV output values from a 380V discharge event 10 centimeters away.

One last example of a threshold detection method involves the partial discharge form of ESD. During power outages, stator windings are inspected for visual damage, but may not identify discharge sites within the ground-wall insulation. One way at the time of the relevant paper [11] to help detect these locations was the Tennessee
Valley Authority (TVA) probe. This probe was (at the time) the only way to detect these PD locations using electromagnetic fields. It consisted of a 'loop-stick' antenna. The larger the antenna response, the closer the antenna was to the discharge location (or the discharge was potentially larger). Unfortunately, the TVA antenna only had about a 5MHz frequency response and as such had problems with directionality and in providing comparative results between windings. The authors presented a discharge locating (DL) probe that has greater spatial resolving power. The DL probe used a capacitive-type sensor which was preferentially sensitive to near-field radiation. The probe itself was a 10 centimeter by 0.5 centimeter copper strip on a plexiglass substrate. On either side of the strip and on the back of the substrate were copper grounds. Due to the short length of the antenna it was sensitive up to hundreds of MHz. Since signals above 50MHz were highly attenuated through the stator windings, detecting in the 100 MHz range gave better proximity detection. After the antenna, a microprocessor triggered on events of predetermined amplitude and counted them. In this way the antenna was slowly moved along the windings to determine which ones had breakdowns [11].

Several authors used antennas attached to an oscilloscope to simply investigate ESD events, or to distinguish between ESD events and other types of electromagnetic interference, not necessarily locate them. In general, the various authors used either monopoles or loops to detect the ESD. Other popular antennas for characterization purposes included V-dipoles and horn antennas for increased directionality and flatness of response [29] [30] [31].
Takai et. al. [12] presented both a method to discriminate between ESD events and other sources, and a method similar to the threshold detection methods to find the origin of the ESD event. The authors suggested using between 5 and 50 millimeter long monopoles to measure the electromagnetic waves emanating from the discharge point. For their results, they used a 25 millimeter antenna. They then measured the pulses with a 1.1 GHz analog bandwidth oscilloscope and used the fact that ESD events tended to be single events to distinguish between sources. Their detector recorded the peak value, polarity, date, and time of the ESD events and could detect ESD events from as far away as 2 meters.

Munoz et. al. [28] were also interested in both characterizing the ESD event and detecting it to solve ESD issues on a manufacturing line. The authors built a loop antenna to detect the ESD, and then compared three industry ESD stress models as detected by the antenna. The loop antenna was constructed from a fan grill and was 10 centimeters in diameter. During testing the loop was oriented perpendicular to the ESD event. The paper was unclear as to the definition of ‘perpendicular’. The ESD events were able to be distinguished from other events by the distinctive fast rise time, high amplitude, and exponential decay rate. Three different models were used and compared: the Human Body Model, Charge Device Model, and Machine Model. The peak amplitudes of these models correlated well to that picked up by the loop antenna. The authors hoped that in the future this would help identify ESD events by type, and thereby help pinpoint the problem faster. The authors used the setup to identify one part of the production line that showed ESD events: one part of a
machine turned out to be building up significant charge during the process and discharge fields were picked up by the loop antenna only in its vicinity.

The most complex method for detecting ESD involves trying to locate the event through a form of triangulation. Section 2.5 will cover the theory and mathematics behind one particular technique for doing this. One paper that provided a different method for locating ESD explored the topic of locating lightning discharges, which is basically a two-dimensional problem. The authors of this particular paper detected lightning pulses with three E-field disk antennas separated by 10 meters on axis. Since lightning typically occurs in multiple strokes, several events were detected each time. The time delay between the antennas was evident for a specific pulse. The authors converted the recorded time domain data into the frequency domain using the Fast Fourier Transform (FFT). They then performed a cross-correlation and determined the phase differences at various frequencies. This in turn allowed a calculation of the angles between the antenna baselines and the lightning discharge. Since only three antennas were used only the azimuth and elevation were able to be determined, not the distance to the discharge [32].

2.5 Location of Transient Events by Time Difference of Arrival

Rather than use an FFT and cross-correlation method to locate an ESD event for this thesis, a Time Difference of Arrival (TDoA) method was chosen. This is a method that uses multiple antennas attached to an oscilloscope. Since the antenna locations
are known, the time differences between when the ESD waves hit the various antennas provide information on where the initial discharge might be located. Two main papers explored this topic. After the summaries of these papers, more in-depth theory will be presented.

The first paper, by Lin, DeChiaro, and Jon, put forth a reverse GPS-like location of the discharge event [33]. Four antennas were used in conjunction with an oscilloscope and a computer program. The antennas were arranged on an orthogonal axis system, one at the origin, and the other three located 50 centimeters from the origin on the x-, y-, and z-axes. The antennas used were 5 centimeter whip monopoles and were attached to equal length coaxial cables 10 feet long. The antenna orientations were all in the z-direction. For larger dimensions, a second system was built with 3 meters between antennas. The oscilloscope used had 5GS/s resolution.

Once an event was detected by the antenna and oscilloscope system, a least-squares curve fitting was used to find the first peak of the incoming pulse. The TDoA’s between this first pulse and the subsequent pulse arrivals at the other antennas were then recorded. The position of the discharge was determined by solving a system of vector equations. The resulting equations (optimized for their specific case) used by the authors are shown here [33].

\[
(a_i^2 + a_j^2 + a_k^2 - d^2)r^2 - 2(a_i b_{i1}^2 + a_j b_{j1}^2 + a_k b_{k1}^2)r + (b_i^4 + b_j^4 + b_k^4) = 0 \quad (2.3)
\]
Where \( a_i(i=1,2,3) \) was defined in terms of two arrival times: \( a_i = c(t_i - t_0)/2 \) and represented half the distance difference between each non-origin antenna and the origin antenna, with \( c \) being the speed of light. The next parameter, \( b_i \), was defined as

\[
b_i^2 = c_i^2 - a_i^2,
\]

with \( c_i \) being equal to half the position vector of the \( i^{th} \) antenna. The final location of the ESD source was then given by the following equation [33].

\[
x_i = \frac{b_i^2 - a_i r}{d}, i = 1,2,3
\]  

(2.4)

The authors claimed a 1 centimeter by 1 centimeter by 1 centimeter resolution in detecting the ESD event using this method, under tightly controlled conditions. The authors also went into detail on pulse shape and polarity. For their setup, far-field radiation was assumed. Their reduced equations for the EMF induced on the antennas indicated that the pulse shape should be the same for each antenna, just arriving at different times. The peaks were used to determine the location of the discharge because the authors believed they were free from waves reflected by surrounding objects (multi-path).

Even though the electromagnetic wave-front that was generated by the discharge contained contributions from all the current density elements in the radiating structure, the authors determined that the major element in the leading edge came from the discharge point.
During the analysis of the spatial resolution, the authors determined that once the discharge takes place outside the boundaries defined by the antennas, the error increased dramatically. The error went from 1 centimeter to 10 centimeters as quickly as half the baseline distance away (25 centimeters away for a 50 centimeter system). The shape of the error profile did not change when the baseline distance changed. The authors determined that the best antenna distribution was to have the discharge within the defined space of the antennas. An industry ESD gun was used to generate the sparks.

A second important paper on this topic was by Bernier, Croft, and Lowther [34]. Whereas it was assumed the previous authors [33] used a closed-form solution to the TDoA problem, Bernier et. al. used successive approximation to solve the system of equations to locate the ESD event.

The discharge was located by 'reverse GPS' where there were four receivers instead of four transmitters. Every pair of antennas has a time delta between them that defines a hyperbola, where the intersection of the hyperbola is the solution point.

The authors used three 25mm long whip antennas at the end of 10ft coaxial cables (only 2D location was considered in this paper). A commercial CDM (charged device model) tester was used to generate the spark. The signals were detected with a 2Gs/s scope. Their measurement point was the peak of the first pulse measured on each channel. The method used to determine the actual point was to (1) start at a
'seed' location, then (2) calculate the sum of squares of the differences between the actual time delays and those predicted from the guessed point. (3) Next the first and second derivatives of the error function were calculated and (4) Newton's method was applied to the first derivatives to provide a better guess at the location where the first derivatives were equal to zero. (5) These (2-4) steps were repeated using the result of the fourth step until the desired accuracy was achieved. All steps were then repeated using different starting points until the error function was within the preferred tolerance.

Further experiments were performed in an actual production room. The spark source used in these cases was a Coleman lantern igniter (spark-gap). The antennas were placed 6 feet from the origin, two on the x-axis, and one on the y-axis. Their accuracy in this case was within 6 inches when line-of-sight was present between the source and the antennas. When metal objects were placed between them, no solution or wrong solutions were found.

Both of the above papers use Time Difference of Arrival to locate an ESD event. This method is also known as hyperbolic positioning, and is used in GPS, radar, and other navigation systems. In developing the ESD location method for this thesis, the general formulation from the paper, “Simple Solutions for Hyperbolic and Related Position Fixes” was followed closely [4]. The relevant parts of this paper are presented here in their entirety.
Assume there are three base stations (measurement antennas in the ESD location application) located orthogonal to each other with one station at the origin. Let $V$ be the signal velocity, $T_{ab} = T_a - T_b$ and $T_{ac} = T_a - T_c$ be the differences in the times of signal arrival at the station pairs A, B and A, C, respectively [4].

\[
\sqrt{x^2 + y^2 + z^2} - \sqrt{(x-b)^2 + y^2 + z^2} = V \cdot T_{ab} = R_{ab} \tag{2.5}
\]

\[
\sqrt{x^2 + y^2 + z^2} - \sqrt{(x-c_x)^2 + (y-c_y)^2 + z^2} = V \cdot T_{ac} = R_{ac} \tag{2.6}
\]

where $R_{ab}$ and $R_{ac}$ are range differences from the navigation position to the stations, converted from the measured time of arrival differences. Transposing the first terms to the right-hand sides of (2.5) and (2.6), squaring and simplifying, one obtains [4]

\[
R_{ab}^2 - b^2 + 2b \cdot x = 2R_{ab} \sqrt{x^2 + y^2 + z^2} \tag{2.7}
\]

\[
R_{ac}^2 - c^2 + 2c_x \cdot x + 2c_y \cdot y = 2R_{ac} \sqrt{x^2 + y^2 + z^2} \tag{2.8}
\]

where $b$ and $c = \sqrt{c_x^2 + c_y^2}$ are the lengths of station baselines. These two equations, when squared, represent two hyperboloids of revolution with foci at A, B and A, C, respectively. By equating (2.7) and (2.8) and simplifying, one obtains [4]

\[
y = g \cdot x + h \tag{2.9}
\]
where [4]

\[ g = \frac{\{R_{ac} \left( \frac{b}{R_{bh}} \right) - c_x\}}{c_y} \]  \hspace{1cm} (2.10)

\[ h = \frac{\{c^2 - R_{ac}^2 + R_{ac} R_{ab} (1 - \left( \frac{b}{R_{ab}} \right)^2)\}}{2c_y} \]  \hspace{1cm} (2.11)

Substituting (2.9) into (2.7), one obtains [4]

\[ z = \pm \sqrt{d \cdot x^2 + e \cdot x + f} \]  \hspace{1cm} (2.12)

where [4]

\[ d = -\{1 - \left( \frac{b}{R_{ab}} \right)^2 + g^2\} \]  \hspace{1cm} (2.13)

\[ e = b \cdot \{1 - \left( \frac{b}{R_{ab}} \right)^2\} - 2g \cdot h \]  \hspace{1cm} (2.14)

\[ f = \frac{R_{ab}^2}{4} \{1 - \left( \frac{b}{R_{ab}} \right)^2\}^2 - h^2 \]  \hspace{1cm} (2.15)

Equation (2.10) defines a plane orthogonal to the station baselines. The ESD event location must lie in this plane. Now the position vector for the event location depends on a single unknown parameter \( x \) [4],
By adding a fourth station (antenna) the unknown parameter can be calculated, giving the final position for the ESD event. This position will be at the intersection of three hyperboloids. The fourth station, C', with the associated timing measurement $T'_{ac}$, and stations A and B, defines another plane on which the location lies. Using the same technique as above, but with a primed coordinate system, a second position vector is found [4].

$$\tilde{R} = x \cdot \tilde{i} + (g \cdot x + h) \tilde{j} \pm (\sqrt{d \cdot x^2 + e \cdot x + f}) \tilde{k} \quad (2.16)$$

Taking the scalar product of (2.16) and (2.17) with the unit vector $\tilde{j}'$ and equating the results, one obtains [4]

$$g' \cdot x + h' = (gx + h)(\tilde{j} \cdot \tilde{j}') \pm \sqrt{d' \cdot x^2 + e' \cdot x + f'} \quad (2.18)$$

Squaring and simplifying, one obtains [4]

$$p \cdot x^2 + q \cdot x + r = 0 \quad (2.19)$$

where [4]
\[ p = d \cdot (\vec{k} \cdot \vec{j'})^2 - \{g' - g \cdot (\vec{j} \cdot \vec{j'})\}^2 \] (2.20)

\[ q = e \cdot (\vec{k} \cdot \vec{j'}) - 2\{g' - g \cdot (\vec{j} \cdot \vec{j'})\} \{h' - h \cdot (\vec{j} \cdot \vec{j'})\} \] (2.21)

\[ r = f \cdot (\vec{k} \cdot \vec{j'})^2 - \{h' - h \cdot (\vec{j} \cdot \vec{j'})\}^2 \] (2.22)

With \( x \) known as the solution of (2.19), \( y \) and \( z \) follow from (2.9) and (2.12), respectively. Since there are two equations involving square roots, the system of equations results in up to four different possible locations. However, at least two of the possible solutions can be easily discounted given general knowledge of where the ESD event should be located (i.e. within the system of antennas).
Chapter 3. Selection of Antennas for ESD Detection

3.1 Important Aspects of Antennas for Detection of ESD Events

There are many types of antennas that could be used to detect an ESD event. Depending on the application, one antenna type may be preferred over another. When trying to detect an ESD event in the far-field, horn antennas or log-periodic dipole arrays may be the most suitable. When trying to detect ESD in a small area, commercially available near-field probes may be better suited.

In order to select the appropriate antenna for the location of an ESD event within a 3D space several things must be considered. Among the most important antenna aspects are size, directionality, frequency response and gain, and proximity effect.

If the only requirement of this thesis was to detect an ESD event, then a large, high-gain, broadband antenna would be ideal. Horn antennas and LPDA’s have been used with great success to do this. However, the antennas for use in locating an ESD event in a product, such as a printer, need to be small enough to be easily moved and handled. This is in part due to the number of antennas (four) being used. It is also potentially desirable to have the ability to place multiple antennas within a product. This automatically rules out anything much larger than 10cm in diameter, with something smaller than a few centimeters being ideal.

In addition to the above size limitations, there is also an uncertainty factor to consider. The larger the antenna is, the more uncertain it is which part of the antenna
detects the first rising edge of the ESD pulse. An antenna that is electrically small (or close to it) should reduce the uncertainty when calculating the location of the ESD event.

An example to illustrate the uncertainty of a larger antenna is the performance of an LPDA compared to that of a small dipole. An LPDA has several dipoles with a common feed point. If an ESD event has a frequency spectrum that is not broadband and flat, only a few elements of the LPDA will be excited: those elements that are approximately one-half wavelength at the frequencies corresponding to the ESD event [35]. So for any given ESD event it is unclear what part of the LPDA is excited and therefore an error is introduced in the known path length of the signal traveling from the antenna to the oscilloscope. Alternatively, a small dipole has only one element to be excited, so the uncertainty on the path length is greatly reduced. As long as all four antennas are identical, this may not be an issue, but is best to avoid it. Therefore by extending this principle, the smaller the antenna, the less uncertainty there should be in locating the ESD event as long as the other antenna aspects are good enough.

Directionality is also a very important aspect of the antenna. Ideally the antennas used to locate an ESD event should be isotropic, since there may not be any foreknowledge of the probable location of the ESD event. From a practical standpoint this is not fully achievable as any antenna probe used will have a coaxial
cable attached to it. The best solution is to find antennas that are symmetrical in as many axes as possible.

Both frequency response and gain are among the most important aspects of the antennas. Most ESD events create a broadband high-frequency radiated field. In order for an ESD event location system to work properly there must be enough information at the oscilloscope to decipher when the event occurs. This means that as much electric or magnetic field energy as possible must be picked up. In general, a high gain antenna would be best. Also antennas that are efficient up to a high frequency (several Gigahertz) are required. This is because the faster the rise time of the first ESD energy to arrive at the oscilloscope, the less uncertainty there is when determining the timestamp of the event. If the antennas used do not have a high enough bandwidth then the measured rise times will be lower because of the lowered high frequency content.

The last important aspect to consider when choosing an antenna for detecting and locating an ESD event is the proximity effect of the antennas. In other words, how close can the antennas be before they begin to influence the oscilloscope measurements? The size of most products this system would be utilized with is on the order of 20cm on a side to 75cm on a side. As long as the antennas are placed outside this region the proximity effect of the antennas should not be an issue. However, if two or more antennas are placed in a small region due to other constraints it is necessary to know the uncertainties that are introduced.
In this section size, gain, and frequency response will be considered in the selection of antennas. In the next section, Analysis of Selected Antenna, the directionality and proximity effect will be explored further.

### 3.2 Antennas Considered for Detection

In order to narrow the choices for antennas, the easiest aspect to look at first is size. It is obviously impractical to use a one meter long LPDA, unless the goal is to locate a discharge in a large room. Even so, a horn antenna may be a better choice for that application. Ideally, the antennas used for locating an ESD event should be quite small for ease of use and reduction in location uncertainty.

There are two cost effective alternatives try: a commercially available near-field antenna kit, and fabricated ‘home-made’ antennas. Of the choices available, the ETS near field kit (model 7405) was chosen as a starting point. This kit contains a selection of E-Field and H-Field antennas. The E-Field antenna selection consists of a small monopole (6mm long) and a medium sized (3.6 cm diameter) spherical antenna. The H-Field antenna selection consists of three loop antennas (diameters 1cm, 3cm, and 6cm). Figure 3.1 shows a picture of the antennas selected for analysis. The 1cm loop antenna was omitted from consideration.
The H-field antennas contain a single turn, shorted loop inside a balanced E-field shield. The loops are constructed by taking a single piece of 50 ohm, semi-rigid coax from the connector and turning it into a loop. When the end of the coax meets the shaft of the probe, both the center conductor and the shield are 360 degree soldered to the shield at the shaft, forming a single shorted turn. A notch is then cut at the high point of the loop, creating a balanced E-field shield of the coax shield [36]. See Figure 3.2 for a diagram of the antenna construction.
The larger ETS E-field antenna (spherical shaped, Figure 3.3) shaft is constructed of a length of 50 ohm coaxial cable with a 50 ohm resistor terminating the end. This is to present a conjugate termination to the 50 ohm coax. The center conductor is extended beyond the 50 ohm termination and attached to a 3.6 cm diameter metal ball [36].

![Figure 3.3: ETS E-field Spherical Antenna Construction Detail [36]](image)

The smaller ETS E-field antenna (stub monopole, Figure 3.4) is made of a single piece of 50 ohm, semi-rigid coaxial cable which has 6 mm of the center conductor exposed at the tip. This short length of center conductor serves as a monopole antenna to pick up E-field emanations with high H-field rejection [36].

![Figure 3.4: ETS E-field Monopole Antenna Construction Detail [36]](image)

The smallest ETS H-field antenna was not investigated since it most likely would perform similarly to the other two H-field antennas, but with much lower sensitivity.
Figure 3.5 shows the antenna characteristics of the ETS near-field antennas. All but the largest loop antenna has a resonant frequency above 1GHz. This is promising since ESD events generate significant radiated energy above 1GHz.

In addition to the commercially available antennas, it was decided to construct some alternate antennas for comparison. This alternative was attractive because it was cheaper to fabricate four custom antennas than to purchase enough commercial antenna kits just to get four antennas of the same type. Two different types of antennas were constructed.

The first antenna constructed was a whip-style monopole. The shield of a small semi-rigid 50 ohm coaxial cable (RG-402) was cut 6cm away from the end of the cable. This detached shield was then soldered to the center conductor of the cable. The
shield still intact formed the image plane for the fed center conductor. In order to provide a makeshift balun for the antenna the coaxial cable was then wrapped through a solid core ferrite (or toroid) several times. This was to prevent RF currents from traveling along the shield. Upon exiting this ferrite the coaxial cable was cut and an SMA connector was attached. In order to protect the feed point shrink-tubing was applied to the middle of the monopole. The resulting antenna is shown in Figure 3.6. The purpose of this antenna was to create a high frequency monopole tuned to the frequency band where the most emissions occur when measuring radiated emissions from 1-2GHz.

![Figure 3.6: Constructed Antennas](image)

The second antenna constructed, also shown in Figure 3.6, was a short, fat monopole. A 1cm diameter brass cylinder was cut to 1.2cm in length. Then a small hole was drilled through the center of the cylinder. The center conductor of a semi-rigid 50 ohm coaxial cable (RG-402) was soldered into this hole. Shrink-tubing was again
used at the feed point to protect the antenna. The purpose of this antenna was to create a wide-bandwidth high-frequency probe with high E-field gain.

3.3 Response of Antennas to a Pulse Source

One way to evaluate all of the antennas is to measure their response to a single consistent source. This source should be highly repeatable so that there is no ambiguity about how the various antennas respond to the given stimulus. The source should also have a high enough signal that the results are clear. This could be easily achieved with a signal generator, amplifier, and a horn antenna. However, the results would be for only a single frequency, and would not necessarily give enough information on the suitability of the antennas for eventual use in detecting a broadband signal.

Instead of using a constant signal, a repeating pulse was used. This provided the requisite repeatability of results, but also provided a broadband frequency characteristic. The repeating pulse was created with a Tektronix AWG2040 Arbitrary Waveform Generator. The output of the AWG2040 was attached to a HP8447D amplifier in order to get more signal to the antenna, an ARA DRG-118A horn. The HP amplifier has an operational frequency from 0.1MHz to 1300MHz, and the antenna operates in the 1GHz to 18 GHz range. An E-field horn antenna was used because ESD events usually create stronger electric than magnetic fields [17]. Figure 3.7 shows the setup for evaluating the near-field antennas with this equipment.
After data was taken with this setup, a different amplifier was used in place of the HP8447D in order to try and get better data (higher amplitude output). This second amplifier (OPHIR 5142) has an operational frequency from 0.7GHz to 3GHz.

Figure 3.7: Near-Field Antenna Evaluation Setup

Figure 3.8a shows the signal generated by the AWG2040. The pulse is roughly 5 nanoseconds in width with rise and fall times on the order of 1 nanosecond. This results in a signal with frequency content in the gigahertz range (see Figure 3.8b), which is where the near-field probes needed to be evaluated.
Figure 3.8a: AWG2040 Pulse Output (Time Domain)

Figure 3.8b: AWG2040 Pulse Output (Frequency Domain)
Unfortunately, the AWG2040 could not provide enough signal to the antenna. Therefore the HP amplifier was necessary. Since the amplifier frequency range started at 0.1 MHz, the DC value of the pulse was stripped off. However, this did not matter since the edges of the pulse were preserved. Figure 3.9a shows the resulting signal out of the HP amplifier provided to the antenna. As well as increasing the signal strength, the rise and fall times were halved to roughly 0.5 nanoseconds. It was unclear why this occurred. In addition to the spikes due to the rising and falling edges of the input signal other artifacts were introduced in the amplifier stage, but were not detrimental to the results since all that was necessary was a solid first pulse edge. Figure 3.9b shows the same measurement point as Figure 3.9a, except with the OPHIR amplifier. Instead of clearly defined spikes where the pulse edges were, the amplifier seemed to ‘ring’ due to the pulse.
Figure 3.9a: HP 8447D Amplifier Pulse Output
The resulting frequency spectra of the signals in Figures 3.8-3.9 are shown in Figure 3.10. The AWG2040 and both amplifiers were measured with a Rohde & Schwarz FSP Spectrum Analyzer. As a reference point, the spectrum analyzer noise floor was also measured (no input signal). The AWG2040 trace had lower amplitude than the noise floor trace because of the settings used for that particular measurement (10dB input attenuation instead of 20dB). The additional attenuation for the other traces was necessary to prevent potential damage to the instrumentation, but the AWG2040 output was low enough that the attenuation had to be reduced to view its output spectrum. Also, the amplitude jump at 3GHz is due to the spectrum analyzer switching internal receivers at 3GHz.
Figure 3.10: Frequency Spectra of Pulse Source Stages

Both amplifiers should be sufficient to evaluate the near field antennas with respect to a pulse source since both produce a broadband source in the 1-2GHz range. However, the OPHIR amplifier has a much wider frequency response and therefore creates a broadband source that extends up to 3.5GHz. Also, notice that the ringing and its harmonics seen at the output of the OPHIR amplifier are noticeable in the frequency domain as spikes.

The HP and OPHIR amplifiers were used to test the response of the near field antennas, with the test setup shown above in Figure 3.7. There were two antennas attached to the TDS 7404 oscilloscope. One antenna was used to trigger the measurement and was kept constant throughout the testing. The other antenna was
evaluated based on this trigger event. The constructed fat monopole was used as a trigger since there were several available.

Each antenna was tested in the maximum gain configuration and the minimum gain configuration. The source antenna was in vertical polarization. For the E-field antennas this meant broadside testing would be the maximum and end-fire would be the minimum. For the H-field antennas, the E-field polarization (loop axis facing perpendicular to antenna) was maximum and the H-field polarization (loop axis facing towards antenna) was minimum (see Figure 3.11). This was mainly because the source antenna was an E-field antenna, which caused a bias against H-field antennas for this testing.

![ARA DRG-118A](image)

**Figure 3.11: Loop Antenna Orientations**

First, the HP amplifier was used to test the near field antennas. The trigger antenna was placed 20 cm away from the horn antenna and slightly offset to one side, with the measurement antenna slightly offset to the other side (also 20 cm from the horn antenna). Figure 3.12 shows all of the trigger waveforms. The consistent waveform
indicates that any variation in results between the tested antennas should be due to factors other than source variations.

Compare Figure 3.12 with the waveform in Figure 3.9a. Notice that there is energy present at the same location in time, but that there is a ringing also present. This is possibly due to the non-ideal impedance matching between the trigger antenna and the oscilloscope as well as the length of coaxial cable between the two.

Figures 3.13a, 3.13b and 3.13c show the resulting waveform with each test antenna in the maximum gain configuration: broadside for the E-field antennas and perpendicular to the source for the H-field antennas. Figures 3.14a, 3.14b, and 3.14c
show the minimum gain waveforms: end-fire for the E-field antennas and facing the source for the H-field loop antennas. For easy comparison, the graphs all have the same vertical scale.

![Graph showing Factory E-Field Antenna Response to HP8447D Pulse Source, High Gain Orientation](image)

**Figure 3.13a: Factory E-Field Antenna Response to HP8447D Pulse Source, High Gain Orientation**
Figure 3.13b: Factory H-Field Antenna Response to HP8447D Pulse Source, High Gain Orientation

Figure 3.13c: Constructed E-Field Antenna Response to HP8447D Pulse Source, High Gain Orientation
Figure 3.14a: Factory E-Field Antenna Response to HP8447D Pulse Source, Low Gain Orientation

Figure 3.14b: Factory H-Field Antenna Response to HP8447D Pulse Source, Low Gain Orientation
From the above graphs it is easy to see that the three best antennas, from a signal strength standpoint, are the factory spherical antenna, the constructed monopole, and the constructed fat monopole. Unfortunately, the source signal strength is not high enough to fully evaluate the antennas. The received signal in the low-gain orientations is not even above the noise floor for some of the antennas.

In addition to the signal strength evaluation of the antennas, a quick pseudo-directivity measurement was made. The maximum directivity is typically defined as the ratio of the maximum radiation intensity to the average radiation intensity [37]. For comparison purposes, a quick directivity measurement can be calculated by finding the ratio of the maximum peak-to-peak voltage in a high gain orientation to
the maximum peak-to-peak voltage in a low gain orientation. Ideally the antennas used in locating a pulse or spark should be isotropic, and would have a pseudo-directivity value of 1. The antennas should be isotropic (have the same response in all directions) because otherwise information coming from one or more directions may not be received. This would then lead to an inaccurate result. However, since most antennas won’t be isotropic, a value close to 1 is desirable. Table 3.1 shows the peak-to-peak received signal amplitudes for each antenna in both the high gain and low gain orientations. The resulting pseudo-directivity value is also listed.

<table>
<thead>
<tr>
<th>Table 3.1: Antenna Response to HP8447D Pulse Source Comparison</th>
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</thead>
<tbody>
<tr>
<td><strong>High Gain Orientation Pk-Pk Amplitude (mV)</strong></td>
</tr>
<tr>
<td>Factory Medium Loop</td>
</tr>
<tr>
<td>Factory Monopole</td>
</tr>
<tr>
<td>Factory Large Loop</td>
</tr>
<tr>
<td>Factory Sphere</td>
</tr>
<tr>
<td>Constructed Fat Monopole</td>
</tr>
<tr>
<td>Constructed Monopole</td>
</tr>
</tbody>
</table>

Even though the directivity calculation for the factory loop antennas and the factory monopole antenna in the low gain orientation are listed, the results are not meaningful since there was not enough signal received in the low gain orientation to get above the noise floor. Of the three antennas that did receive enough signal, the constructed monopole had the best directivity. This was unexpected as there should have been very little signal picked up in the end-fire orientation. It is possible constructed monopole was not accurately positioned. Due to the length of the constructed
monopole, even a small tilt away from the end-fire orientation could provide enough vertical length to pick up a good signal.

In order to get a better result, the Ophir amplifier was used to create the pulse to the source antenna. The test setup was the same as with the HP amplifier, except the receive antennas were placed 60cm away from the source antenna instead of 20cm away. The reason for this was that the field produced by the source antenna with the Ophir amplifier was significantly greater than that of the HP amplifier. Figure 3.15 shows the trigger pulses for the Ophir amplifier source. Figures 3.16a, 3.16b, and 3.16c show the resulting waveform with each test antenna in the maximum gain configuration (same as with HP amplifier) and Figures 3.17a, 3.17b, and 3.17c show the resulting waveform with each test antenna in the minimum gain configuration.

![Figure 3.15: Trigger Waveforms for OPHIR 5140 Amplifier Source Setup](image)
Figure 3.16a: Factory E-Field Antenna Response to OPHIR 5140 Pulse Source, High Gain Orientation

Figure 3.16b: Factory H-Field Antenna Response to OPHIR 5140 Pulse Source, High Gain Orientation
Figure 3.16c: Constructed E-Field Antenna Response to OPHIR 5140 Pulse Source, High Gain Orientation

Figure 3.17a: Factory E-Field Antenna Response to OPHIR 5140 Pulse Source, Low Gain Orientation
Figure 3.17b: Factory H-Field Antenna Response to OPHIR 5140 Pulse Source, Low Gain Orientation

Figure 3.17c: Constructed E-Field Antenna Response to OPHIR 5140 Pulse Source, Low Gain Orientation
From the above graphs it is easy to see that the three best antennas, from a signal strength standpoint, are still the factory spherical antenna, the constructed monopole, and the constructed fat monopole. Unfortunately, even with the more powerful amplifier, the source signal strength is barely high enough to evaluate the antennas. Table 3.2 shows the peak-to-peak received signal amplitudes for each antenna in both the high gain and low gain orientations for the OPHIR 5140 amplifier source. The resulting pseudo-directivity value is also listed.

<table>
<thead>
<tr>
<th>Table 3.2: Antenna Response to OPHIR 5140 Pulse Source Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="mV" alt="high gain orientation pk-pk amplitude" /></td>
</tr>
<tr>
<td>Factory Medium Loop</td>
</tr>
<tr>
<td>Factory Monopole</td>
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<tr>
<td>Factory Large Loop</td>
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<tr>
<td>Factory Sphere</td>
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<tr>
<td>Constructed Fat Monopole</td>
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<tr>
<td>Constructed Monopole</td>
</tr>
</tbody>
</table>

Even though the directivity calculation for the factory loop antennas and the factory monopole antenna in the low gain orientation are listed, the results are still barely meaningful since there was still a low signal received in the low gain orientation, just enough to get above the noise floor. The constructed monopole again had the best directivity. During this experiment the directivity of the two constructed antennas were very similar and along with the factory spherical antenna all had good pickup of the signal.
3.4 Response of Antennas to a ‘Spark’ Source

A spark source was used for the next comparison between the antennas. By using a spark source as part of the comparison and selection process, we can start to get an idea how the final antenna system will perform when trying to locate a spark within a product. It is not useful to select an antenna that works great when an E-field antenna is used as the source, but does not pick up the fields from an actual spark. Unfortunately spark sources are inherently less repeatable than the pulse sources used previously, and therefore introduce another variable in the comparison process.

There are several ways to generate an impulsive source that is similar to a spark. The first possibility was to use an ESD ‘gun’, such as those used in IEC 61000-4-2 [5] ESD Immunity testing (Figure 3.18). These ESD guns have a highly repeatable waveform and would be easy to use. Unfortunately the guns are usually relatively large and, in addition to creating the ESD event, they also generate high electromagnetic fields from the generating circuit. These high fields from the electronics could introduce errors into the measurement process if the antennas pick up those fields before the fields generated by the spark event. Several papers have used this kind of setup before with success, but it was decided that the gun would only be used if no better alternative was found.
A second possible way to generate an impulsive source like a spark was to use a surge arrestor (Figure 3.9). Several of these devices were available in the lab, so an attempt was made to use them as the source. Basically these devices have a predetermined air gap within a gas-filled capsule. As soon as the voltage across the arrestor leads reaches 90V a spark jumps across the gap. In this way the arrestor protects circuitry from high voltage surges by shunting the voltage to ground. A 100V bench top power supply was used to supply the voltage to the surge arrestor. By changing the current limiting on the power supply the voltage would creep up, discharge and then creep back up. This created a repeating spark source that was small and had a very repeatable waveform. It was also very easy to place in various different positions. Unfortunately, the electromagnetic fields generated by this setup were barely measurable by any of the antennas beyond about 15 cm. While this would be barely acceptable for this part of the experiments, it would not be useful for future experimentation.
The third option considered for the spark source was a piezoelectric igniter, more commonly known as a gas-grill lighter. These devices are simply piezoelectric crystals encased in a plastic housing. Within this housing, a spring-loaded hammer (triggered by a plunger button) strikes the crystal. When the hammer strikes the crystal a high voltage (typically 15-17kV) is generated. Two leads exit the plastic housing. One lead was extended with copper tape until it almost touched the other lead (Figure 3.20). That way when the plunger button was pushed a spark was generated between the two leads.
The resulting waveform was relatively repeatable but had significant variations in amplitude. This amplitude variation was probably dependant on how hard the hammer hit the piezoelectric crystal and how close the leads were when the spark occurred. In order to counteract this, while performing the experiments there was a trigger antenna present that was not moved. The amplitude and waveform characteristics were observed and data was only taken for instances where the resulting trigger waveforms were very similar.

The small size of the igniter was ideal for flexible placement. Also, the ease of generating the spark was highly desirable. Therefore the igniter was used as the spark source for this study and subsequent experiments.

Once the spark generator method was chosen, the antennas were evaluated. The evaluation method was the same as for the pulse generator method outlined above. A trigger antenna was placed 60cm away from the spark generator. The evaluated antennas were also placed 60cm away from the spark generator, offset from the trigger antenna by about 20cm. Figure 3.21 shows the trigger pulses for the spark generator source. Figures 3.22a, 3.22b, and 3.22c show the resulting waveform with each test antenna in the maximum gain configuration (same as with pulse source investigation) and Figures 3.23a, 3.23b, and 3.23c show the resulting waveform with each test antenna in the minimum gain configuration.
Figure 3.21: Trigger Waveforms for Spark Generator Setup

Figure 3.22a: Factory E-Field Antenna Response to Spark Generator, High Gain Orientation
Figure 3.22b: Factory H-Field Antenna Response to Spark Generator, High Gain Orientation

Figure 3.22c: Constructed E-Field Antenna Response to Spark Generator, High Gain Orientation
Figure 3.23a: Factory E-Field Antenna Response to Spark Generator, Low Gain Orientation

Figure 3.23b: Factory H-Field Antenna Response to Spark Generator, Low Gain Orientation
Just like with the pulse source, it is easy to see that the three best antennas, from a signal strength standpoint, are still the factory spherical antenna, the constructed monopole, and the constructed fat monopole. Maybe not surprisingly, the loop antennas performed better with the spark source than when the E-field antenna was used as a source. This is because the E-field antenna was designed to maximize the E-field, not H-field. With the spark source there was not only the high E-field generated by the spark itself, but also significant H-field generated by the current loop created by the spark generating circuit.

The amplitude of the received waveforms was an order of magnitude higher for the spark source. This was unsurprising since the source voltage was several orders of
magnitude higher than with the pulse source, even if the antenna (igniter leads) was not as efficient.

Another thing to note in the plots above is the frequency content. The first complete sinusoidal period in the constructed monopole waveform of Figure 3.22c is roughly 410 picoseconds, which corresponds to a frequency of 2.44 GHz. The first complete sinusoidal period in the constructed fat monopole waveform is 340 picoseconds, corresponding to a frequency of 2.94 GHz. This frequency range is consistent with what is expected for a spark source. The results also suggest that the constructed fat monopole may have a higher frequency range than the constructed monopole. However, the factory spherical antenna beat out both constructed antennas at 320 picoseconds and 3.12 GHz. The higher frequency range is desirable since a higher received frequency content leads to a faster rising edge, and therefore a more accurate measurement and a potentially better resolution of the spark location.

Table 3.3 shows the peak to peak amplitudes of the waveforms in both high and low gain orientations. The table shows results similar to the pulse source. However, there was an additional variation in the spark source that was not present for the pulse source, namely that the source amplitude was not as consistent as with the pulse source. This can be seen in Figure 3.21. In order to compensate for this and provide for a better comparison between the antennas, the peak to peak amplitude results were normalized to the highest amplitude trigger waveform. The trigger waveform that had the highest amplitude was the one associated with the constructed monopole in
the high-gain orientation, so that measurement was unchanged. Table 3.4 shows the results of this normalization.

<table>
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<th>Table 3.3: Antenna Response to Spark Source Comparison, Raw Numbers</th>
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<td></td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Factory Monopole</td>
</tr>
<tr>
<td>Factory Medium Loop</td>
</tr>
<tr>
<td>Factory Large Loop</td>
</tr>
<tr>
<td>Factory Sphere</td>
</tr>
<tr>
<td>Constructed Monopole</td>
</tr>
<tr>
<td>Constructed Fat Monopole</td>
</tr>
</tbody>
</table>

The antennas in both Table 3.3 and Table 3.4 were ordered in ascending peak to peak amplitude level for the high-gain orientation. By far, the constructed fat monopole had the best performance from a sheer amplitude standpoint. When considering directivity, however, the factory large loop antenna was the best. This was surprising since the H-field loop should have had a null (just like the end-fire orientation for a dipole). Even so, the lowest measurement by the constructed fat monopole was still

<table>
<thead>
<tr>
<th>Table 3.4: Antenna Response to Spark Source Comparison, Normalized to Highest Amplitude Trigger Waveform</th>
</tr>
</thead>
<tbody>
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<td></td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Factory Monopole</td>
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<tr>
<td>Factory Medium Loop</td>
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<tr>
<td>Factory Large Loop</td>
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<tr>
<td>Constructed Monopole</td>
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<tr>
<td>Factory Sphere</td>
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<tr>
<td>Constructed Fat Monopole</td>
</tr>
</tbody>
</table>
higher than the highest loop antenna measurement. Of the E-Field antennas, the factory sphere had the best directivity. This is probably due to the highly symmetric nature of the antenna.

### 3.5 Frequency Response of Considered Antennas

Once the antennas were evaluated in the time domain using pulse sources and a spark source, they were evaluated in the frequency domain. The frequency response of the antennas will indicate the relative gain of the antennas as well as the useable frequency range. The best antenna to use will have both a high frequency range and good gain.

The frequency response of the antennas was measured using a Rohde and Schwarz ZVK Vector Network Analyzer. The S21 network parameter (insertion loss) was measured from 1-5GHz. 1GHz was the lowest frequency used because only sources with frequency content above 1GHz contribute to emissions problems. 5GHz was used as the upper frequency limit for two reasons: the measurement limitations of the oscilloscope (5 Gigasamples per second per channel), and that, as a lab, any emissions above 5GHz have not been shown to be due to static pops.

The measurement setup is shown in Figure 3.24. The setup consisted of the network analyzer, short low-loss cables attached to each analyzer port, a source antenna, and a receive antenna. The network analyzer was calibrated (through, open, and short) with
the ‘through’ measurement consisting of the low-loss cables connected together.

Other than the frequency range, all other settings were the default analyzer settings.

![Diagram of Network Analyzer S21 Insertion Loss Measurement Setup]

**Figure 3.24: Network Analyzer S21 Insertion Loss Measurement Setup**

The first measurement was taken with a horn antenna on each port, facing each other in the same polarization. This provided a reference against which the near-field antennas were judged. The separation between the antennas for all measurements was approximately 20 cm. Further separation was not possible due to the short length of the low-loss cables. Figures 3.25a-c show the resulting measurements of the antennas in their high gain orientation, with the horn antenna response as a reference in all the graphs. Figures 3.26a-c show the resulting measurements of the antennas in their low gain orientation.
Figure 3.25a: Factory E-Field Antenna Frequency Response, High Gain Orientation

Figure 3.25b: Factory H-Field Antenna Frequency Response, High Gain Orientation
Figure 3.25c: Constructed E-Field Antenna Frequency Response, High Gain Orientation

Figure 3.26a: Factory E-Field Antenna Frequency Response, Low Gain Orientation
Figure 3.26b: Factory H-Field Antenna Frequency Response, Low Gain Orientation

Figure 3.26c: Constructed E-Field Antenna Frequency Response, Low Gain Orientation
In the Figures above, it is clear that near-field antennas with the best response (highest gain and fewest resonances) are the factory sphere, constructed monopole, and the constructed fat monopole. It was expected that the loops would not perform well when using an E-field source for the frequency response. The high gain received amplitude (insertion loss) of the H-field antennas was equivalent to the low gain received amplitude of the E-field antennas.

In addition to the high insertion loss, the H-field antennas exhibited several resonances. This would introduce ‘blind spots’ if these antennas were used to detect an ESD event. For instance, if an ESD source was not as broadband due to resonant metallic structures around the source, and the resulting frequency spectrum lined up with a resonance in the H-field antennas, they may not pick up enough signal to determine the location. Unfortunately, the E-field antennas also showed some of this resonance behavior, but mostly only in the low gain (end-fire) orientation.

The factory monopole performed poorly in both orientations (broadside and end-fire), while the factory sphere and the two constructed antennas showed good frequency characteristics. All three antennas were relatively flat, especially in the broadside orientation. In order to better show this the data from the horn antenna was subtracted from the data of these three antennas, creating a response that is normalized to a horn antenna response. Figure 3.27a shows the data for the broadside orientation and Figure 3.27b shows the data for the end-fire orientation.
Figure 3.27a: Horn-Antenna-Normalized Frequency Response, High Gain Orientation

Figure 3.27b: Horn-Antenna-Normalized Frequency Response, Low Gain Orientation
The flatness of the normalized frequency response show above for the three best antennas was good, and was similar between all three. The gains of the constructed monopole and constructed fat monopole were similar for the broadside orientation, staying within about 5dB of each other. One exception was a frequency band where the constructed monopole was resonant. Over the entire frequency band, the constructed fat monopole tended to have slightly better gain characteristics than the constructed monopole. The constructed fat monopole had better gain than the factory sphere by 5-10 dB over the entire frequency range.

In the low gain end-fire orientation, the normalized frequency response of the three antennas showed few differences between each other. The differences were mostly due to the resonances in each antenna occurring at different frequencies. The constructed fat monopole was a little worse than the other two antennas, since it had more resonances. Also, as the frequency increased the gain increased. This gain increase was probably due to a larger influence by the cables, rather than the intended antenna structure.

### 3.6 Location of ESD Event in One-Dimensional Space

The next step in selecting a near-field antenna for ESD event location is determining which antennas have the least inherent measurement error. One method of doing this is to locate an ESD event in one-dimensional space. This can be done with two near-field antennas, a spark source (in this case a handheld piezoelectric igniter), and a fast
oscilloscope. In addition to finding the inherent measurement error of the antennas, this setup will give an idea what accuracy to expect from the full three-dimensional locator setup. The antenna evaluation cannot be easily separated from an evaluation of the measurement techniques, so before the antennas are evaluated, some discussion of the measurement technique is appropriate.

The one-dimensional locator setup uses two antennas of the same type, spaced a known distance apart. In this case the separation distance was 1 meter. Each antenna was connected to the oscilloscope with the same length of coaxial cable. This was to minimize path length errors in the measurement setup and to postpone the creation of a calibrator for the antenna and cable combination.

Two locations for the spark source were chosen to evaluate the antennas. The first location was in line with the antennas, but not between them. The actual location used was about 20 centimeters beyond one of the antennas (see Figure 3.28). Obviously the antennas would not be able to locate the spark source in this case. The resulting time difference of arrival for the two antennas would only be able to measure the distance between them. However, this is a useful result in evaluating the accuracy of the antenna measurement system in one dimension. All errors that would normally take place in the full blown three-dimensional locator system are present, such as errors in the placement of the antennas, path length errors due to slightly different coaxial cable lengths, path length differences in the oscilloscope input.
channels, and human error in interpreting the resulting waveforms. In addition, any errors created by inaccurate location of the spark source would be removed.

The second location chosen for evaluation was to place the spark source 30cm from one of the antennas. This experiment would show the ability of the antennas to actually locate the spark source, as well as show the additional variability introduced by the uncertainty of the spark source placement. Figure 3.28 shows the test setup.

![Figure 3.28: One-Dimensional ESD Event Location Setup](image)

In order to locate a spark source between the two antennas, a time difference of arrival (TDoA) method is used. The method is similar to what will be used for the three-dimensional case, but the mathematics are much simpler. When the spark ignites, the created electromagnetic waves travel in an expanding sphere, inducing a voltage (or current, depending on the antenna) on the antenna when it arrives. The EM waves travel at the speed of light (roughly $2.99 \times 10^8$ m/s in free space) and will
arrive at the antennas at different times. By measuring this time difference of arrival, the location of the spark source in this simple setup is estimated.

The EM waves created by the spark source at position x will travel a distance, $d_1$, before hitting one of the antennas at time $t_1$. For ease of use, $t_1$ is defined as zero. The waves will continue to expand an additional distance, $d_2$, and at a time $t_2$ will hit the second antenna. Therefore $d_2$ can be found by multiplying the time difference of arrival, $t_2 - t_1$, by the speed of light, $c$. Once $d_2$ is known, $d_1$ can be calculated by subtracting $d_2$ from the distance between the antennas and dividing the result by a factor of two. Since both distances are now determined, the location of the spark relative to the antennas is known. Figure 3.29 shows a graphical representation of this.

\[ \text{Total Antenna Separation Distance} = 2d_1 + d_2 = 1m \]
\[ d_2 = (t_2 - t_1) c \]
\[ d_1 = \frac{(1 - d_2)}{2} \]

Figure 3.29: Graphical Representation of Variables for Calculating 1-D Location
Determining the time difference of arrival is key to locating the spark source. Given the complex nature of the waveforms, what part of the waveform should be defined as the time the electromagnetic field arrived at the antenna? In an ideal case, the waveform seen by both antennas would be identical except in amplitude, and any point in the waveform could be chosen. Unfortunately this rarely occurs due to asymmetric spark source antenna structures and the fact that the receive antennas will not be identical or have identical polarizations. Several papers have stated that the first rising edge and pulse of the received waveform is due to the spark itself, with subsequent parts of the waveform possibly due to the spark source antenna structure and surrounding materials [33] [34]. Therefore the first part of the waveform should be used to determine the time stamps. But which is more accurate, using the pulse peak or the rising edge? Both methods present interpretation problems, but is either one better than the other?

Using the setup in Figure 3.28, two waveforms were captured using the constructed fat monopole antennas. Figure 3.30 shows these waveforms with three possible measurement points labeled on each one. The very first distinct pulse peak from Antenna 2 is labeled as point 1a. Since this peak is the first one, it is the most likely one to correspond to the initial spark. A similar point is marked on the Antenna 1 waveform as 1b. This point is not very useable since the amplitude has greatly reduced by the time the field reaches Antenna 1. Points 2a and 2b correspond to the zero-crossing of the rising edge of the next pulse. Finally, points 3a and 3b correspond to the peak of the highest amplitude initial pulse. This pulse is quite
useable due to the amplitude being high enough to easily measure on the Antenna 1 waveform.

![Example Waveforms, Spark Source at Location 1 Using Constructed Fat Monopole](image)

**Figure 3.30: Example Waveforms, Spark Source at Location 1 Using Constructed Fat Monopole**

As an illustration for why no other points were considered for measurement, Figure 3.31 shows the same waveforms as Figure 3.30, but with the Antenna 1 waveform time-shifted by about 3.3 nanoseconds so that it lines up with the Antenna 2 waveform. The figure shows that the waveform is not exactly repeated at both antennas, and that the further in time you get from the initial pulse, the less likely the high-frequency information will remain the same. Therefore, the rest of the one-dimensional investigation will calculate the time difference of arrival values from two of the previously notated measurement points (2a, 2b, 3a, and 3b from Figure 3.29).
There may not be much difference regarding which measurement point is used, but when dealing with a system where 30 picoseconds of time error equates to almost a centimeter of distance error, it should be investigated. As a note for further investigation, a cross-correlation algorithm may be useful if the waveforms are similar enough (although polarity differences may make this more complicated).

![Antenna Waveforms](image)

**Figure 3.31: Example Waveforms, Time-Shifted, Using Constructed Fat Monopoles**

In order to compare the antennas, five measurements each were taken with the spark source in the two locations shown in Figure 3.28. The calculated distance based on the TDoA for location #1 should have corresponded to 1 meter, and the calculated distance based on the TDoA for location #2 should have corresponded to 0.4 meters.
This 40 centimeter distance would then indicate a spark location 30 centimeters from the antenna which first received the pulse \( (d_1 = [1 - 0.4]/2 = 0.3 \text{ meters}) \).

For both locations, the measurements resulted in values close to expected (within a few centimeters for most samples). Since location #1 did not have the added source of error due to the spark source placement (the source was outside the antennas so there was no error introduced by the source being closer to one antenna or the other), the accuracy of that measurement should have been slightly better than that of location #2. Figure 3.32 shows the average error (in centimeters) from the expected measurement. Both peak and edge methods of TDoA measurement are listed. Figure 3.33 shows the same data as a percentage error from the expected measurement. The medium-sized factory H-field antenna had the best absolute accuracy of all the antennas in one run of the experiment, with an average error of 0.5 centimeter, and the constructed monopole had the worst at about 3 centimeters. However, the repeatability of the measurements may be just as important, and both those antennas had about the same best- to worst-case measurement delta (about 1 centimeter). For the loop antennas, the ‘parallel’ indicates that the face of the loop is parallel to the one-dimensional axis and ‘perpendicular’ indicates the opposite.
Figure 3.32: Average 1-D Location Measurement Error

Figure 3.33: Average 1-D Location Measurement Error Percentage
The error for location #1 was slightly higher (in absolute terms) than that of location #2 for most of the antennas. Only the constructed fat monopole performed equally well in both locations. This is possibly due to the fact that the amplitude of the received electromagnetic field was higher for both antennas when the spark source was in location #2, which allowed a more accurate placement of the oscilloscope cursors to measure TDoA. Another thing to notice in Figure 3.32 is that the edge detection method seems to perform slightly better than the peak detection method. Figure 3.33 further illustrates that not much difference was seen between the two locations. Since the measured TDoA for location #2 was half that of location #1, the percentage error differences were about two times higher for location #2 even though the absolute error was very similar.

Figure 3.34 combines the error for both locations into a single average absolute error. This simplifies the data to show that there is inconclusive evidence which measurement method (peak or edge detection) provides the best accuracy. However, experience while taking the data was that identifying appropriate peaks to measure was much quicker and easier than identifying the appropriate place to measure an edge.
Figure 3.34: Comparison of Peak and Edge Detection Methods

One last metric to introduce before selecting the antenna for further investigation is the repeatability and precision of the antennas. Average accuracy is important, but this should also be coupled with the ability to have faith in the measurement for successive experiments. Figure 3.35 shows the standard deviation of each antenna for each location and measurement method.
Several interesting conclusions can be drawn from the data in Figure 3.35. For the E-field antennas, the peak detection method was mostly better than the edge detection method, especially for location #1. For the H-field antennas, the results were more inconclusive, but the peak method was still better. Also, with the exception of the constructed monopole antenna, the H-field antennas tended to be more variable than the E-field antennas. The increased variability of the H-field antennas likely is largely due to the reduced amplitudes (lower gain) seen by these antennas. Also, even though all antennas saw higher fields when the spark was at location #2 (which should have decreased variability), location #2 tended to be more variable. This increased variability of location #2 was probably directly attributable to the variation
in the spark source location. Each successive measurement may have had the source closer to one antenna or the other.

Table 3.5 shows another evaluation of the location error associated with each antenna. The table takes into account both spark source locations and both measurement methods. The first section of Table 3.5 shows the best case (average) results of all the measurements for each antenna, and the second section does the same for the worst case results. The first column lists the absolute error from expected and the second column lists the standard deviation. Assuming the one dimensional case applies to all three axes independently, the three dimensional error and precision for each antenna is extrapolated using the following simple equation:

\[
Error_{3D} \approx \sqrt{3 \times Error_{1D}^2}
\]  

(3.1)

After tabulating this data, the three best antennas from an error perspective are the medium H-field, the large H-field, and constructed fat monopole antennas. From a repeatability standpoint, the three best antennas are the constructed fat monopole, the factory monopole, and the large H-field antennas. In general, the best antennas should have between one and two centimeters of error in three dimensions. This amount of error is acceptable when trying to find a source within a product, since most structures that create a spark are larger than a couple centimeters.
Table 3.5: Antenna Error Comparison

<table>
<thead>
<tr>
<th></th>
<th>Best Case 1D Error (cm)</th>
<th>Best Case 1D Precision (cm)</th>
<th>Extrapolated 3D Error (cm)</th>
<th>Extrapolated 3D Precision (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory Monopole</td>
<td>1.30</td>
<td>0.24</td>
<td>2.24</td>
<td>0.41</td>
</tr>
<tr>
<td>Factory Sphere</td>
<td>1.32</td>
<td>0.29</td>
<td>2.28</td>
<td>0.51</td>
</tr>
<tr>
<td>Constructed Monopole</td>
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<td>0.48</td>
<td>3.91</td>
<td>0.83</td>
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<tr>
<td>Constructed Fat Monopole</td>
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<td>0.00</td>
<td>1.84</td>
<td>0.00</td>
</tr>
<tr>
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<td>0.24</td>
<td>2.21</td>
<td>0.41</td>
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<tr>
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<td>0.29</td>
<td>2.23</td>
<td>0.51</td>
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<table>
<thead>
<tr>
<th></th>
<th>Worst Case 1D Error (cm)</th>
<th>Worst Case 1D Precision (cm)</th>
<th>Extrapolated 3D Error (cm)</th>
<th>Extrapolated 3D Precision (cm)</th>
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</thead>
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<tr>
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<td>1.46</td>
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<td>2.23</td>
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</tr>
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<td>3.00</td>
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</tr>
<tr>
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<td>Med. Loop Parallel</td>
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<td>Med. Loop Perpendicular</td>
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<td>2.19</td>
<td>2.52</td>
<td>3.80</td>
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</table>

3.7 Antenna Selection Conclusions

Selecting the correct antenna for continued experimentation was a matter of compromise, since no antenna clearly excelled in all areas (size, directionality,
frequency response and gain, proximity effect, and potential inherent error). In the size category (and the related category of flexibility of use), the best antenna was the constructed fat monopole. While the construction was not that different from the factory spherical antenna, it was quite a bit smaller and had a much more flexible cable attachment. This provides the ability to be placed into tight spaces within a product.

When considering directionality, there was no clear consistent best antenna. All of the antennas showed comparable directionality at some point in the testing. However, the amplitude of the received signal during the pulse source and spark source testing revealed that the E-field antennas clearly picked up the fields better. This high sensitivity trumped directionality, especially since the end-fire sensitivity of the E-field antennas in general were on par with the H-field antennas in their best orientation.

The frequency response testing showed a preference for the E-field antennas, although the result was skewed by using an E-field source for the Network Analyzer source channel. The constructed fat monopole had the best overall gain of all the antennas, and the E-field antennas in general had fewer resonances (flatter frequency response) than the H-field antennas.

Finally, error and precision were considered. The proximity effect was not factored into the decision yet, but will be evaluated in the next section once an antenna is
chosen. When attempting to measure a one-dimensional distance with the antennas, the H-field antennas and the constructed fat monopole antenna had the lowest error, and the constructed fat monopole, factory monopole, and large loop antenna had the best precision.

Based upon the above results, most of the above antennas should be acceptable to use as long as a signal can be picked up, but a good compromise for the three-dimensional ESD event locator antenna is the constructed fat monopole. Ease of construction, ease of use, high gain, good frequency response, and good error performance make this antenna the best choice.
Chapter 4. Analysis of Selected Antenna

4.1 Repeatability of Antenna Construction

The selected antenna was the constructed fat monopole. Since this antenna was made in the lab and not a factory, it was possible that there would be differences between antennas once enough were constructed to meet the needs of the ESD event location setup. Three different methods were employed to determine if there were significant differences: visual inspection, a Time Domain Reflectometer (TDR) measurement, and a frequency sweep of each antenna with a network analyzer.

Three more antennas were carefully assembled using brass cylinder stock and RG-402 coaxial cable. See Section 3.1 for more details on the original antenna construction. All four final antennas had very similar coaxial cable lengths between the brass cylinder and the SMA connector. Upon visual inspection of the final product, there were some small differences between the antennas. The holes drilled through the brass cylinders were not all exactly on center. Also, even though the manner in which the center conductor was soldered to the brass was similar for all antennas, the resulting solder flow was not identical in all cases. Lastly, there were small differences in coaxial cable length between the brass cylinder and the SMA connector. Figure 4.1 shows a broadside view of all four antennas and Figure 4.2 shows the tops of all four antennas. Ideally these small differences would not adversely impact the ESD event location system, or at worst the differences could be compensated.
Once the antennas were visually inspected, the next step was to use a TDR to compare all four antennas. A TDR measures the impedance of a transmission line by launching a short voltage pulse down the transmission line and measuring the pulse reflections that travel back to the TDR [38]. The output impedance of a TDR is typically 50 ohms. Wherever an impedance discontinuity exists in the transmission line, part of the energy from the pulse will be reflected back to the TDR. The amplitude and polarity of the reflected pulse is determined by the ratio of the transmitted voltage to the reflected voltage. TDR measurements are made on a relative scale using the reflection coefficient [38]:

Figure 4.1: Broadside View of Constructed Fat Dipoles

Figure 4.2: Top View of Constructed Fat Dipoles
\[
\rho = \frac{Z_i - Z_o}{Z_i + Z_o}
\]  

(4.1)

Where \(Z_o\) is the characteristic impedance of the transmission line and \(Z_i\) is the impedance of the discontinuity, and \(\rho\) is the reflection coefficient. Since it takes a finite time (depending on the speed of light in the transmission line) for the pulse to travel to the discontinuity and travel back to the TDR, the resulting impedance is typically plotted as a function of (round-trip) time. The above equation can be rearranged so that the unknown impedance can be determined and displayed by the TDR [38].

\[
Z_i = Z_o \frac{1 + \rho}{1 - \rho}
\]  

(4.2)

Two things can be determined by using a TDR to compare the antennas. First, the length of the coaxial cable sections of the antennas can be compared. Second, the discontinuity where the brass cylinder meets the center conductor can be examined for any differences. Since the antennas will be used in a system where long cables will be present between the antenna connector and the oscilloscope, some measurements were made with these cables present. For the TDR measurement in Figure 4.3, each antenna was measured with two lengths of coaxial cable (roughly 1.3m in length each) included between the antenna and the TDR. Since all eight cables were purchased from the same company (same part number), they should have
been very close in actual length. All measurements were performed with a Tektronix 11801B Digital Sampling Oscilloscope (20ps rise-time launch pulse). The vertical scale on all TDR plots is the reflection coefficient ($\Gamma$).

Figure 4.3: TDR Measurement of Four Constructed Fat Dipoles with Two Intermediate Coaxial Cables

The vertical center of the plot in Figure 4.3 indicates 50Ω. Whenever a coaxial cable is connected to another cable, a discontinuity appears. This discontinuity is indicated by a slight ‘bump’ in the plot. Depending on the type of discontinuity, the bump may be high (inductive discontinuity) or low impedance (capacitive discontinuity). In Figure 4.3 it is easy to see the two cables and the short monopole antenna. The end of the antenna is indicated by high impedance (kΩ). The time it takes to travel one direction down the cables is indicated on the plot. All four antennas, with associated cables, were plotted on the same graph. From this vantage point there is no
discernible length or discontinuity difference between the antennas. According to the TDR plot, the lengths of the cables are on the order of 1.13m (speed of light x 0.6 x 6.3ns) since the speed of light in coaxial cables is roughly 60% that of free space. Next, Figure 4.4 shows a TDR measurement with only the antennas attached (no intermediate cables).

![TDR Measurement of Four Constructed Fat Dipoles](image)

**Figure 4.4: TDR Measurement of Four Constructed Fat Dipoles**

Figure 4.4 shows some small differences between the four antennas. These differences show up at the end of the antenna where the brass cylinder is soldered to the center conductor. According to the TDR, the lengths of the four antenna coaxial cables are on the order of 9.2cm (speed of light x 0.6 x 512ps) and are very similar. However, due to the differences at the end of the antenna, it is possible that not all
four antennas are terminated exactly the same. Figure 4.5 shows a close-up of the end of the antenna showing a zoomed in view of the end discontinuity.

Figure 4.5: TDR Measurement of Constructed Fat Monopole End Discontinuity

Two of the antennas have very similar discontinuities, while the other two are completely different. This discontinuity difference may be due to the differences in the soldering on each antenna, such as how far the solder traveled down the center of the brass cylinder. The differences may also be caused by the proximity of the beginning of the brass cylinder to the end of the coaxial cable shield. In particular, the purple trace that rises in impedance and then dips down before rising again could be due to this. A larger separation between the brass and the coaxial cable shield could present high impedance as the center conductor gets farther from the coax shield, then lower impedance as the capacitance of the brass cylinder to the coax
shield influences the impedance. This should not cause a problem, but if it does, more antennas could be constructed.

The second difference clearly shown in Figure 4.5 is the length difference between the four antennas. Three of the antennas have roughly the same length of coaxial cable attached to the brass cylinders. The fourth antenna is a little shorter, with a one-way time difference of about 24 ps. This corresponds to about 4.3 mm. This is a small difference, but if uncompensated could introduce about 7.2 mm ($4.3 \sqrt{3}$) of error into a TDoA measurement.

The next method used to compare the four constructed antennas was to measure their frequency response. The same setup as in Section 3.5 (Figure 3.23) was used, where the frequency response was measured from 1GHz to 5GHz. The broadside and both end-fire configurations were compared. Figure 4.6a shows a picture of the co-polarized broadside measurement and Figure 4.6b shows the resulting measurement.

Figure 4.6a: Co-Polarized Broadside Frequency Response Setup
In Figure 4.6a, the horn antenna (ARA DRG-118A) and the short fat monopole were both vertically polarized. The feed-point of the monopole was approximately 20cm from the front face of the horn antenna, and roughly centered on the horn antenna feed-point. The Vector Network Analyzer (Rohde & Schwarz ZVK) was attached to both antennas and set up to measure S21 from 1GHz to 5 GHz. The horn antenna was mounted on a tripod and the monopole was taped to a PVC pipe.

The frequency responses shown in Figure 4.6b from all four constructed fat monopole antennas were almost identical from 1 GHz to 4GHz. Between 4GHz and 5GHz the constructed antennas (with the exception of Antenna 1) showed similar curves, but separated by a few dB. Antenna 1 had an additional null just above 4.5GHz. The
initial intent for the ESD location system was to have all four constructed antennas oriented vertically with the potential ESD event contained within the antenna system. Therefore this polarization would be one of the two most relevant. The other most important polarization is shown in Figures 4.7a and 4.7b, where Figure 4.7a shows the cross-polarized broadside measurement setup, with Figure 4.7b showing the resulting measurement.

Figure 4.7a: Cross-Polarized Broadside Frequency Response Setup
Figure 4.7a shows the horn antenna vertically polarized with the constructed fat monopole horizontally polarized. As in the previous measurement the feed-point is about 20cm away from the front of the horn and centered on the horn feed-point.

The frequency response in Figure 4.7b shows that all four constructed antennas have very similar responses from 1GHz up to 3GHz, and show a generally similar profile from 3GHz to 5GHz. Antennas 1 and 2 both had frequency nulls just above 4 GHz. Next, Figures 4.8a and 4.8b show the top end-fire setup and measurement, and Figures 4.9a and 4.9b show the bottom end-fire case.
Figure 4.8a: Top End-fire Frequency Response Setup

Figure 4.8b: Top End-fire Frequency Response
Figure 4.9a: Bottom End-fire Frequency Response Setup

![Bottom End-fire Frequency Response Setup](image)

Figure 4.9b: Bottom End-fire Frequency Response

In both end-fire cases the feed-points of the constructed fat monopole antennas were approximately 20cm away from the front face of the horn antenna. In the bottom
end-fire case this resulted in the constructed fat monopole’s coaxial cable running very close to the front edge of the horn antenna.

Not much signal was expected from the top end-fire case, and this is shown in Figure 4.8b. However, the bottom end-fire case showed higher signal levels than the co-polarized broadside measurement. This was most likely due to the proximity of the coaxial cable to the horn antenna, and was expected since the cable shield was meant to be the image plane for the monopole. This result showed that the coaxial cable could introduce some error in the measurement if the ESD event is close to one of the cables.

Figure 4.10 shows the four different frequency measurements for Antenna 1. As was found in Section 3, the Co-polarized broadside measurement of the constructed antennas showed a fairly flat frequency response. Another important result was that all four antenna orientations showed a good response in the 1GHz to 2GHz range.
The visual inspection combined with the TDR and Network Analyzer measurements indicated that the four antennas were very similar. Based on this, no new antennas were constructed.

### 4.2 Antenna Proximity Effect

Once the construction of the antennas was verified, the next step was to check the proximity effect of the antennas when used as a system. In this context, proximity effect is used to describe how close an antenna can be to another antenna(s) without causing a change in its measurement characteristics. The first test was to see if the impedance characteristics (as measured by the TDR) changed.
One of the antennas was measured by the TDR as in Section 4.1. This trace was saved and then to simulate the worst case antenna proximity case, the other three antennas were spaced closely together next to the first antenna. The three antennas that were not attached to the TDR were terminated in the measurement channels of an oscilloscope. Figure 4.10a shows a diagram of this setup, and Figure 4.10b shows a picture of the antenna configuration. Figure 4.11 shows the TDR comparison.

**Figure 4.10a: TDR Antenna Proximity Effect Setup**

**Figure 4.10b: TDR Antenna Proximity Effect Close-Up Picture**
The antennas were spaced less than 1cm apart. Placing them further apart showed no discernible difference in the impedance plot. As the antennas approached the antenna that was attached to the TDR, the impedance began to get ‘lumpier’ on the upwards slope (near the center of Figure 4.11). However, once the antennas were settled in place this effect improved.

The effective length of the antenna was changed by about 8ps when it was placed in close proximity to the other three antennas. This is not significant since this corresponds to about 2.4mm in free space, and part of the change is attributable to small, unavoidable, changes in the positioning of the measured antenna. At most this would be a second order effect in the final ESD event location system error.
Next, the frequency response measurement was performed, first on one antenna then with the other three antennas spaced in close proximity to the first antenna. The measured antenna was placed approximately 20cm away from the front of the horn antenna, vertically polarized (broadside). The other three antennas were spaced around a PVC pipe in the same orientation. Two different configurations were used. The first configuration was with the measured antenna placed closest to the horn antenna. The second configuration was with measured antenna placed furthest away from the horn antenna, but still 20cm from the front edge. Figures 4.12a and 4.12b show these two configurations. Figure 4.13 shows a picture of configuration 1. The extra antennas were attached to an oscilloscope in order to terminate the antennas in a typical instrument configuration.

Figure 4.12a: Network Analyzer Proximity Effect Measurement Configuration #1
Once both configurations were measured, they were compared to a measurement with only a single antenna present. The results are shown in Figure 4.14. The frequency response of the single antenna alone was very similar to that of configuration #1.
Once the antennas were rotated around the PVC pipe such that the measured antenna was behind the other antennas (configuration #2), the frequency response changed. This change was exhibited by about a 10dB broadband drop in received signal in three general frequency bands: 1.5GHz to 2GHz, 2.5GHz to 3GHz, and 3.5GHz to 4.5GHz. The reduced signal amplitude in configuration #2 was most likely due to a ‘shadowing’ (aperture blocking) effect by the other antennas, and possibly by the PVC pipe.

![Graph showing frequency response and amplitude](image)

**Figure 4.14: Network Analyzer Measurement of Antenna Proximity Effect**

Based upon the results obtained from the TDR and Vector Network Analyzers, the chosen antenna design will not have noticeable proximity effect problems. On the TDR, the antennas had to be within 1cm of each other before changes in the antenna
impedance were noticed. It is important to note that this impedance is not directly related to the antenna impedance usually referred to in antenna design.

For the Vector Network Analyzer frequency response in the presence of other antennas, there was a drop in received signal in a certain configuration. However, the antennas were again in much closer proximity than what was expected to be the case for the ESD event location system. For the ESD event location system, the expected application is with the suspected ESD event to be located within the constellation of antennas. As long as care is taken not to place an antenna directly behind another one, there should not be a problem. Even so, if the antennas are in close proximity, the amplitude of the received signal should be high enough that the 10dB reduction will make no difference.

4.3 Method of Moments Modeling of Antenna

The measurement of antenna characteristics can be done through physical means as in preceding sections, or through the modeling of antenna behavior. Modeling of antenna structures can be done using many different methods and sub-methods. There are two main types of computational electromagnetics: numerical methods and high-frequency (asymptotic) methods [39]. Typically, numerical methods are used to model systems that are up to a few tens of wavelengths in size or smaller. The numerical methods include techniques such as the Method of Moments (MoM), Finite-Element Method (FEM), and Finite-Difference Time-Domain (FDTD).
The MoM technique is based on integral equations, either the Electric Field Integral Equation (EFIE) or the Magnetic Field Integral Equations (MFIE). The EFIE is applicable to both open and closed surfaces, but the MFIE is only applicable to closed surfaces [40]. The integral equation problem describes the current distribution on a wire antenna resulting from an arbitrary excitation, with the currents subject to the boundary conditions (either electric field or magnetic field). The MoM is a procedure for approximating these integral equations with a system of simultaneous linear algebraic equations in terms of an unknown current. Once the current is known, the radiation pattern is straightforward to calculate.

Current distributions on the antenna structure are modeled in terms of basis functions and invoking the boundary conditions. The antenna is subdivided into many small sections, with each section’s current described by these basis functions. The basis functions used can vary widely, but the most typical are simple geometric functions such as rectangles, triangles, or sinusoids. These functions can also span multiple current segments.

Several approximations can be used to simplify the calculations. For antenna design, the most common one is the ‘thin-wire’ approximation which assumes that the antenna elements are small enough in diameter (radius $\ll \lambda$) that current elements only have one vector describing their amplitude and direction. For example, a thin vertical antenna would only have z-directed current elements. Two of the most
popular MoM programs use this approximation, Numerical Electromagnetics Code (NEC) [41], and Mini-Numerical Electromagnetics Code (MININEC) [42]. The basic MININEC code is available as a free download at http://www.emsci.com/.

Unfortunately, the antennas selected for the ESD event location system did not meet the requirements for modeling by most free versions of MoM code based on NEC or MININEC. This was because they did not meet the thin-wire approximation. The modeling of the antennas was to occur over the 1-5GHz frequency range. The radius of the brass monopole part of the antennas was 0.005m. At 5GHz this corresponds to about 1/12 wavelength, which is enough for most of these programs to post an error. Therefore it was necessary to use non-free professional electromagnetic modeling software.

The program finally used to model the antenna was EMSIM [43], a MoM electromagnetic field solver developed by IBM. EMSIM uses rooftop current basis functions. EMSIM was developed to perform electromagnetic modeling of circuit board traces and other common structures found in the electronics industry. The solver is capable of modeling any arrangement of rectangular conductors and dielectrics, only limited by available memory and execution time. Since the solver can handle 3D geometries, the user must be careful to use 2D surfaces as much as possible in order to reduce execution time (i.e. a closed metallic cube should be modeled as six 2D surfaces instead of one 3D object).
In particular, the rectangular geometric limitations impacted how the constructed fat monopole antennas were modeled. The constructed antennas were almost exclusively cylindrical in character from the brass cylinder at the feed-point, to the coaxial cable and the hexagonal SMA connector. Instead of modeling the antennas exactly as they were constructed, the model was modified to fit a Cartesian coordinate system, where the cylinders were changed to rectangular boxes.

In order to transform the model from cylinder to box, but without changing the frequency characteristics, the length of each section was kept the same. In addition, the surface area of each section was also kept the same. Therefore, the equation for the surface area of a cylinder was equated to the surface area of a rectangular box to determine the required dimensions. See the following equations for the determination of the brass section dimensions. Since there is no current flow on the xy-plane walls (top and bottom) of the cylinder section, the surface areas of the top and bottom walls were not considered a restricting factor.

\[
\text{Cylinder Sidewall Surface Area} = 2\pi \cdot \text{radius} \cdot \text{length} \\
= 2\pi \cdot 0.476cm \cdot 1.27cm = 3.8cm^2
\]

\[
\text{Box Side Surface Area} = 4 \cdot \text{length} \cdot \text{width} \\
= 4 \cdot 1.27cm \cdot \text{width} = 3.8cm^2 \Rightarrow \text{width} = 0.748cm
\]
Similar calculations were performed on the rest of the antenna model. Table 4.1 shows the dimensions of each section. The resulting antenna model consisted of six distinct sections: (1) the brass cylinder, (2) the feed-point, (3) the coaxial cable between the feed-point and the SMA connector, (4) the SMA connector, (5) the coaxial cable connected to the SMA connector and the ground plane, and (6) the ground plane. A ground plane was chosen as part of the model since it made the simulation simpler and would be part of the actual measurement of the antenna in a semi-anechoic chamber.

<table>
<thead>
<tr>
<th>Table 4.1: Model Section Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass Cylinder</td>
</tr>
<tr>
<td>Feed-point</td>
</tr>
<tr>
<td>1st Coaxial Cable</td>
</tr>
<tr>
<td>SMA Connector</td>
</tr>
<tr>
<td>2nd Coaxial Cable</td>
</tr>
</tbody>
</table>

All sections were metallic, and the source at the feed-point was z-directed 1.0V amplitude with a zero phase component. The second coaxial cable, meant to simulate the connection from the antenna to the oscilloscope, terminated very close to the ground plane. The length of the second coaxial cable was chosen as fairly long for two reasons. The first reason was that the cable between the antenna and the oscilloscope would be on the order of 1-2 meters long in the actual event locator setup. The second reason for the length was to elevate the antenna feed-point sufficiently above the ground plane to reduce any effects from ground reflections since in the event locator setup there would normally either be no ground plane, or the
ground plane would be at least a meter away. Figures 4.15a and 4.15b show the antenna model and a close-up of the feed-point.

Figure 4.15a: Antenna Model (Brass Cylinder, Feed-Point, Antenna Coax, SMA Connector, and Beginning of Oscilloscope Coax)
Once the model was completed, the simulation was run for five frequencies, 1-5GHz in 1GHz increments. The program created its own gridding for each case. As would be expected, the higher frequencies required more resources to model than the lower frequencies. The electric and magnetic fields were calculated at 80cm from the antenna and 300cm from the antenna. The two distances were determined based on the practical limitations for measuring the antenna in an anechoic chamber. The fields were calculated in a sphere centered on the antenna feed-point. Figures 4.16a-c show the maximum field versus frequency for 80cm distance, the xy-plane fields, and the xz- and yz-plane fields (the xz- and yz-plane fields were identical). Figures 4.17a-c show the same data for the 300cm case.
Figure 4.16a: Maximum Field Amplitude (80cm Distance)

Figure 4.16b: XY-Plane Field Amplitude (80cm Distance)
Figure 4.16c: XZ (YZ)-Plane Field Amplitude (80cm Distance)

Figure 4.17a: Maximum Field Amplitude (300cm Distance)
Figure 4.17b: XY-Plane Field Amplitude (300cm Distance)

Figure 4.17c: XZ (YZ)-Plane Field Amplitude (300cm Distance)
The modeling results in Figures 4.16a and 4.17a show a fairly flat frequency response from 1-5GHz, and also indicate, as expected, that the E-field is dominant for the constructed fat monopole antennas. These results broadly agree with the Network Analyzer frequency sweeps in Section 4.1. Figures 4.16b and 4.17b show a uniform field amplitude in the xy-plane, which was expected since the antenna was symmetric in this plane. Figures 4.16c and 4.17c show some lobe characteristics, but nothing severe.

The results show that the constructed fat monopole antenna exhibits good behavior over a broad range of frequencies. The analysis also shows it is a good choice for the ESD event locator system.
Chapter 5. Implementation of ESD Event Locator System

5.1 Preliminary Development with MathCAD Worksheet

The first step in implementing the ESD Event Locator System was to create an easily manipulated worksheet to prove out the theory presented by Bertrand Fang [4] and summarized in Section 2.5. Several readily available programs can implement mathematical equations, such as MATLAB, MathCAD, Maple, and others. MathCAD was chosen for its intuitive use and ability to enter equations in easy-to-read mathematical notation without having to translate into a programming language. However, before starting the MathCAD worksheet, Fang’s equations were re-derived to ensure a full understanding of the theory.

In order to keep the implementation simple, the first draft of the MathCAD worksheet assumed that the receive antennas would be located on orthogonal axes. The first antenna was located at the origin, the second antenna was located on the x-axis, the third antenna was located on the y-axis, and the fourth antenna was located on the z-axis. This simplification made it trivial to calculate the dot products in equations (2.20) through (2.22). For an orthogonal antenna configuration, the dot products simplify to the following:

Since

\[
\tilde{i} = \tilde{i}, \quad \tilde{j} = \tilde{k}, \quad \tilde{k}' = -\tilde{j}
\]

(5.1)

Then,
\[
\vec{j} \cdot \vec{j}' = \vec{j} \cdot \vec{k} = |\vec{j}| \parallel \vec{k}| \cos \theta = 0 \quad (\theta = \frac{\pi}{2}) \tag{5.2}
\]
\[
\vec{k} \cdot \vec{j}' = \vec{k} \cdot \vec{k} = |\vec{k}| \parallel \vec{k}| \cos \theta = 1 \quad (\theta = 0) \tag{5.3}
\]

Once the equations were entered in the MathCAD sheet, a method of testing them was needed. The simplest method was to create a test point in space that would take the place of an ESD event. The way to create this was to calculate the distance to each antenna, convert the distances to time elapsed, and determine the TDoA for the antennas. This data was then fed into the MathCAD sheet and the results compared to the known location of the test point.

The initial point chosen for validation was at (0.4m, 0.4m, 0.4m). The antennas (A, B, C, and C’) were at (0, 0, 0), (1.0m, 0, 0), (0, 1.0m, 0), and (0, 0, 1.0m), respectively. Table 5.1 shows the resulting values for the intermediate coefficients (g, g’, h, h’, etc.). Table 5.2 shows the four possible locations of the test point.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unprimed Value</th>
<th>Primed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>h</td>
<td>0 m</td>
<td>0 m</td>
</tr>
<tr>
<td>d</td>
<td>55.57</td>
<td>55.57</td>
</tr>
<tr>
<td>e</td>
<td>-56.57 m</td>
<td>-56.57 m</td>
</tr>
<tr>
<td>f</td>
<td>13.90 m^2</td>
<td>13.90 m^2</td>
</tr>
<tr>
<td>p</td>
<td>54.57</td>
<td>-----</td>
</tr>
<tr>
<td>q</td>
<td>-56.57 m</td>
<td>-----</td>
</tr>
<tr>
<td>r</td>
<td>13.90 m^2</td>
<td>-----</td>
</tr>
</tbody>
</table>
Notice that the third possibility in Table 5.2 corresponds to the correct result.

However, the test point was symmetric with respect to the three axes, resulting in symmetries in the coefficients shown in Table 5.1. In order to ensure that the chosen test point, due to its symmetry, did not conceal flaws in the MathCAD calculation, a second test point was chosen using the random number generator from MathCAD: 

\[ S = (0.823 \text{m}, 0.174 \text{m}, 0.71 \text{m}) \]. Tables 5.3 and 5.4 show the results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unprimed Value</th>
<th>Primed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>-0.759</td>
<td>0.607</td>
</tr>
<tr>
<td>( h )</td>
<td>0.798 m</td>
<td>0.211 m</td>
</tr>
<tr>
<td>( d )</td>
<td>6.666</td>
<td>6.873</td>
</tr>
<tr>
<td>( e )</td>
<td>-6.031 m</td>
<td>-7.498 m</td>
</tr>
<tr>
<td>( f )</td>
<td>0.953 m²</td>
<td>1.546 m²</td>
</tr>
<tr>
<td>( p )</td>
<td>6.298</td>
<td>-----</td>
</tr>
<tr>
<td>( q )</td>
<td>-6.287 m</td>
<td>-----</td>
</tr>
<tr>
<td>( r )</td>
<td>0.909 m²</td>
<td>-----</td>
</tr>
</tbody>
</table>

Table 5.4: Calculated Potential Locations for \( S=(0.823 \text{m}, 0.174 \text{m}, 0.71 \text{m}) \)

<table>
<thead>
<tr>
<th>Possible Point</th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.823</td>
<td>0.174</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>0.823</td>
<td>0.174</td>
<td>-0.71</td>
</tr>
<tr>
<td>3</td>
<td>0.175</td>
<td>0.665</td>
<td>0.317</td>
</tr>
<tr>
<td>4</td>
<td>0.175</td>
<td>0.665</td>
<td>-0.317</td>
</tr>
</tbody>
</table>
As in the first case, the location of the test point was found by the MathCAD worksheet. Notice that Point 1 was the correct result this time instead of Point 3. This particular test point also highlighted a potential problem with this ESD event location system. How does the user know which answer is correct? More about this will be discussed later, but the answer requires that the user know enough about the probable location of the event to rule out several of the potential locations. For further illustration purposes, Figure 5.1 shows the plot of the four potential locations from Table 5.4. The blue lines are the receive antenna baselines.

![Figure 5.1: Plot of Potential Locations for Test Point S=(0.823m, 0.174m, 0.71m)](image)

Both test point locations were found by the MathCAD worksheet in the orthogonal antenna configuration. Therefore the methodology for finding an ESD event location
using hyperbolic positioning in this configuration was deemed possible. The next step, before implementing the algorithm in C++ code, was to add a non-orthogonal antenna configuration to the MathCAD worksheet and verify its performance.

In this case, a non-orthogonal antenna configuration consisted of allowing the fourth antenna to be placed anywhere in space (except coincident upon another antenna). The third antenna would still be confined to the xy-plane, but was not restricted to the y-axis. The first antenna would still lie at the origin, and the second antenna would be on the x-axis.

The first step in adjusting the MathCAD sheet was to adjust the \( C' \) antenna to lie in a new \( xy' \)-plane. The x-axis was kept the same as before, but the old y- and z-coordinates were combined into a new \( y' \) coordinate in equation (5.4). Using these two new coordinates, the original equations could be used with only slight modification.

\[
x' = x, \quad y' = \sqrt{y^2 + z^2}
\]  

(5.4)

The only additional modification to the original equations was to calculate the dot products in equations (5.2) and (5.3) instead of assigning them a priori. Since the dot products were of two unit vectors, the only component to solve for was \( \cos(\theta) \), where \( \theta \) was the angle between the ABC antenna plane and the ABC’ antenna plane. Using the original, unprimed, coordinates for antenna C’, equations (5.5) and (5.6) calculate
this term. As a check, equations (5.5) and (5.6) provide the correct answers when the fourth antenna is placed on the z-axis.

\[
\vec{j} \cdot \vec{j}' = \frac{y}{\sqrt{y^2 + z^2}} \\
\vec{k} \cdot \vec{j}' = \frac{z}{\sqrt{y^2 + z^2}}
\]  

(5.5)  

(5.6)

Just as in the orthogonal antenna configuration, two test cases were used with the non-orthogonal antenna configuration to quickly verify the MathCAD worksheet. This time, instead of choosing two different test points, the same test point was used in both cases, but with different antenna configurations. The first antenna configuration used an acute angle antenna baseline. The antennas (A, B, C, and C') were at (0, 0, 0), (1.0m, 0, 0), (1.0m, 1.0m, 0), and (0.5m, 0.5m, 1.0m), respectively. Tables 5.5 and 5.6 show the results for a test point located at S=(0.2m, 0.3m, 0.4m).

**Table 5.5: Coefficient Values for Acute NonOrthogonal Antenna Configuration, S=(0.2m,0.3m,0.4m)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unprimed Value</th>
<th>Primed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>0.475</td>
<td>-0.09</td>
</tr>
<tr>
<td>h</td>
<td>0.205 m</td>
<td>0.51 m</td>
</tr>
<tr>
<td>d</td>
<td>4.874</td>
<td>5.092</td>
</tr>
<tr>
<td>e</td>
<td>-5.295 m</td>
<td>-5.008 m</td>
</tr>
<tr>
<td>f</td>
<td>1.024 m²</td>
<td>0.806 m²</td>
</tr>
<tr>
<td>p</td>
<td>4.866</td>
<td>-----</td>
</tr>
<tr>
<td>q</td>
<td>-5.203 m</td>
<td>-----</td>
</tr>
<tr>
<td>r</td>
<td>0.764 m²</td>
<td>-----</td>
</tr>
<tr>
<td>jj`</td>
<td>0.447</td>
<td>-----</td>
</tr>
<tr>
<td>kj`</td>
<td>0.894</td>
<td>-----</td>
</tr>
</tbody>
</table>
Table 5.6: Calculated Potential Locations for S=(0.2m, 0.3m, 0.4m), Acute NonOrthogonal Antenna Configuration

<table>
<thead>
<tr>
<th>Possible Point</th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.846</td>
<td>0.607</td>
<td>0.181</td>
</tr>
<tr>
<td>2</td>
<td>0.846</td>
<td>0.607</td>
<td>-0.181</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

The correct location was one of the results calculated by the MathCAD sheet. Figure 5.2 shows the visual representation of the antennas and resulting potential locations.

The second antenna configuration used an obtuse angle antenna baseline. The antennas (A, B, C, and C’) were at (0, 0, 0), (1.0m, 0, 0), (-1.0m, 1.0m, 0), and (-0.5m, -0.5m, 1.0m), respectively. Tables 5.7 and 5.8 show the results for a test point located at S=(0.2m, 0.3m, 0.4m). Figure 5.3 shows the visual representation.
Table 5.7: Coefficient Values for Obtuse NonOrthogonal Antenna Configuration, S=(0.2m,0.3m,0.4m)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unprimed Value</th>
<th>Primed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>3.241</td>
<td>1.954</td>
</tr>
<tr>
<td>h</td>
<td>-0.348 m</td>
<td>-0.167 m</td>
</tr>
<tr>
<td>d</td>
<td>-5.401</td>
<td>1.282</td>
</tr>
<tr>
<td>e</td>
<td>-2.844 m</td>
<td>-4.447 m</td>
</tr>
<tr>
<td>f</td>
<td>0.945 m$^2$</td>
<td>1.038 m$^2$</td>
</tr>
<tr>
<td>p</td>
<td>-9.22</td>
<td>-----</td>
</tr>
<tr>
<td>q</td>
<td>-2.19 m</td>
<td>-----</td>
</tr>
<tr>
<td>r</td>
<td>0.917 m$^2$</td>
<td>-----</td>
</tr>
<tr>
<td>jj`</td>
<td>-0.447</td>
<td>-----</td>
</tr>
<tr>
<td>kj`</td>
<td>0.894</td>
<td>-----</td>
</tr>
</tbody>
</table>

Table 5.8: Calculated Potential Locations for S=(0.2m, 0.3m, 0.4m), Obtuse NonOrthogonal Antenna Configuration

<table>
<thead>
<tr>
<th>Possible Point</th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible Point 1</td>
<td>-0.205</td>
<td>-1.012</td>
<td>1.141</td>
</tr>
<tr>
<td>Possible Point 2</td>
<td>-0.205</td>
<td>-1.012</td>
<td>-1.141</td>
</tr>
<tr>
<td>Possible Point 3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Possible Point 4</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

Figure 5.3: Plot of Potential Locations for Test Point S=(0.2m, 0.3m, 0.4m), Obtuse NonOrthogonal Antenna Configuration
Based upon the above results, the MathCAD worksheet worked as intended and served the purpose of developing the basic algorithm for the C++ program to follow. The final MathCAD worksheet with the obtuse antenna configuration is found in the Appendix.

### 5.2 ESD Event Locator Program

Once the basic ESD event locator algorithm was developed and verified, the next step was to write a program to perform the same function, but with added functionality. In addition to the base algorithm, the program had the following functions:

- Manual entry of TDoA values
- Manual entry of antenna locations
- Calculation of potential ESD event locations based on manually entered data
- File entry of TDoA and antenna locations for multiple data point calculation
- Results export to file
- 3D display of results, including antenna positions and rough ITE product location
- Oscilloscope Interface
  - Basic setup of oscilloscope for measurement
  - TDoA acquisition based upon manual operation of oscilloscope cursors
  - File export of captured waveforms
The program was developed using Borland C++ Builder. It was designed to interface with a Tektronix TDS7404 oscilloscope via a USB to GPIB converter.

When the program is launched, the screen shown in Figure 5.4 appears. The antenna positions are entered in the text boxes in the upper left hand corner. Some of the boxes are inaccessible to force the user to place the first antenna at the origin, the second antenna on the x-axis, and the third antenna in the xy-plane. The fourth antenna is unrestricted in its placement. The default antenna configuration is orthogonal with 0.5m spacing from the origin to an antenna along the positive x-, y-, z-axes.

![Figure 5.4: ESD Event Locator Program Main Screen](image)

Figure 5.4: ESD Event Locator Program Main Screen
On the left side of the screen in Figure 5.4 is a set of text boxes for entering the corners of a measured product. This assists the user in visualizing the calculated location of the ESD event in relation to the product being measured. By default the product corners are set just inside the antennas.

At the top of the screen there are three text boxes to manually enter the TDoA’s from either a previous set of measurements, or from a manually controlled oscilloscope. Alternatively, if there is an oscilloscope attached, the buttons beside the TDoA text boxes will read the time delta between the cursors. For this to read the correct values, the first cursor must remain on the pulse associated with the first antenna. The second cursor must be moved to the corresponding 2nd, 3rd, or 4th antenna pulses for each measurement. Underneath the TDoA buttons is another button that saves the antenna locations and measured TDoA’s to a file (or appends the data if the file exists). This allows the user take multiple sets of data for later processing.

Next to the TDoA buttons is a set of text boxes for showing the four potential ESD event locations. These are displayed by clicking the “Calculate Position” button. The graph underneath these text boxes displays the antenna locations in blue, the product in yellow, and the potential locations as ‘x’s. The graph can be rotated, set in animation, and exported. Radio buttons next to the location text boxes tell the graph whether to display all potential locations, or just one of the four.
The “Calc Pos from file” button will process a comma-separated file to calculate all potential locations for the given antenna position and saved TDoA’s. The results are saved in another “.csv” file and displayed on the graph. By default, the graph will use the antennas as the product corners unless the “Antennas as Box” checkbox is un-clicked.

The “Plot Points from File” button will also process a comma-separated file, but only for display purposes. This button allows the user to visualize a large set of disparate data. This can be useful when a product may have multiple sources. The file itself consisted of the antenna locations and the (x, y, z) coordinates to be displayed.

The “Setup Oscilloscope” button opens another screen, shown in Figure 5.5. By clicking the “Default Settings” button the oscilloscope will be set up to measure a typical set of ESD event pulses. This button resets the oscilloscope to factory defaults, sets the vertical voltage scale to 50mV/div for each channel, sets the trigger to channel 1 at a 40mV level, and sets the horizontal time scale to 5nsec/div. This setup gives a good starting place for the user to measure an event. Most likely they will need to manually adjust the oscilloscope as well. From this point the user may close the screen and start taking TDoA measurements. However, the user may elect to acquire a few ESD waveforms and save them to a “.csv” file by clicking the “Acquire Traces” and “Save Traces” buttons, respectively. The check boxes select which traces to capture. By default, all traces are acquired. Figure 5.6 shows a screen capture of four traces of acquired ESD events.
Figure 5.5: Oscilloscope Setup and Acquisition Screen

Figure 5.6: Four Traces of Acquired ESD Event
Once the program was developed, it needed to be verified. The scope interface was verified as the program was developed, but the ESD event location algorithm still needed to be validated. This was done in the same manner as the MathCAD sheet validation. One test point was generated (using the MathCAD sheet to find the TDoA’s) for two different nonorthogonal antenna configurations. The first was an acute angle antenna baseline, the second was an obtuse angle antenna baseline.

The first point was chosen randomly using the MathCAD sheet random number generator. The only stipulation was that it was in the positive x-y-z-space since that would be the most typical real-world application. The selected point was $S=(0.295\,\text{m}, 0.608\,\text{m}, 0.183\,\text{m})$. The first antenna configuration was with the four antennas in an acute angle: $(0, 0, 0)$, $(0.5\,\text{m}, 0, 0)$, $(0.2\,\text{m}, 0.4\,\text{m}, 0)$, and $(0.1\,\text{m}, 0.2\,\text{m}, 0.5\,\text{m})$. The resulting TDoA’s for this test were $\text{TDoA } 1-2 = 1.098\times10^{-10} \, \text{s}$, $\text{TDoA } 1-3 = 1.358\times10^{-9} \, \text{s}$, and $\text{TDoA } 1-4 = 4.933\times10^{-10} \, \text{s}$. TDoA 1-2 indicates the time difference of arrival between antenna 1 and antenna 2, relative to antenna 1. These values were entered into the ESD event locator program. The position results are shown in Table 5.9 and a couple screen shots of the program after calculation are shown in figures 5.7a and 5.7b.

### Table 5.9: Calculated Potential Locations for $S=(0.295\,\text{m}, 0.608\,\text{m}, 0.183\,\text{m})$, Acute NonOrthogonal Antenna Configuration

<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible Point 1</td>
<td>0.295</td>
<td>0.607</td>
<td>0.183</td>
</tr>
<tr>
<td>Possible Point 2</td>
<td>0.295</td>
<td>0.607</td>
<td>-0.183</td>
</tr>
<tr>
<td>Possible Point 3</td>
<td>-0.720</td>
<td>-14.573</td>
<td>1.899</td>
</tr>
<tr>
<td>Possible Point 4</td>
<td>-0.720</td>
<td>-14.573</td>
<td>-1.899</td>
</tr>
</tbody>
</table>
Figure 5.7a: ESD Event Locator Program Results, All Locations Displayed

Figure 5.7b: ESD Event Locator Program Results, Correct Location Displayed
From Table 5.9, the correct location was calculated by the program (Position 1). However it was off by a small amount (0.16%) in one dimension: $y=0.607\text{m}$ instead of $y=0.608\text{m}$. This was due to rounding in the TDoA values. The MathCAD worksheet did not have this issue since it used the full precision of the calculated test point TDoA’s, whereas the program only had a four decimal precision for the TDoA entries. Subsequently using higher precision in the TDoA fields reduced this error.

The second antenna configuration was with the four antennas in an obtuse angle: (0, 0, 0), (0.5m, 0, 0), (-0.2m, 0.4m, 0), and (-0.1m, -0.2m, 0.5m). The same test point was used. The resulting TDoA’s for this test were TDoA 1-2 = 1.098e-10 s, TDoA 1-3 = 4.432e-10 s, and TDoA 1-4 = -8.455e-10 s. These values were entered into the ESD event locator program and the position results are shown in Table 5.10. A couple screen shots of the program after calculation are shown in figures 5.8a and 5.8b.

| Table 5.10: Calculated Potential Locations for $S=(0.295\text{m}, 0.608\text{m}, 0.183\text{m})$, Obtuse NonOrthogonal Antenna Configuration |
|-----------------|-----------------|-----------------|
|                | x (meters)     | y (meters)     | z (meters)     |
| Possible Point 1 | 0.295           | 0.608           | 0.183           |
| Possible Point 2 | 0.295           | 0.608           | -0.183          |
| Possible Point 3 | 0.202           | 0.0935          | 0.673           |
| Possible Point 4 | 0.202           | 0.0935          | -0.673          |
Figure 5.8a: ESD Event Locator Program Results, All Locations Displayed

Figure 5.8b: ESD Event Locator Program Results, Correct Location Displayed
With the second antenna configuration, the program calculated the correct test point location (Position 1). This time there was no error to three decimals, even though the same precision was used as in the first antenna configuration. Even though the program was not exhaustively verified, it did perform as expected with the limited test points. As the program was used informal verification took place, and any errors were addressed.

5.3 Locator Program Sensitivity Analysis

Once the program was verified to function as intended, the mass calculation ability of the program was utilized to examine the behavior of the system. Two main experiments were performed. The first experiment was intended to examine whether the antenna configuration made a difference to the error tolerance of the system. The second experiment was designed to determine the sensitivity of the best antenna configuration to inaccurate placement of the antennas.

For the first experiment, four different antenna configurations were investigated:

- Acute Angle Antenna Baseline
- Orthogonal Antenna Baseline
- Obtuse Angle Antenna Baseline
- Planar Antenna Baseline
The method of investigation was to use known test points and then subject the generated TDoA’s to several different distortions and observe the effects on the calculated locations. The test points used were two different circles of points. Both circles were in the xy-plane, one centered on the positive z-axis, and the other centered on the negative z-axis. For all four test cases the circles consisted of ten equidistant points. Table 5.11 shows the coordinates of the test points. The test case TDoA’s were generated from these points relative to each individual antenna configuration.

Table 5.11: Circular Test Point Coordinates

<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0</td>
<td>± 0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.161803</td>
<td>0.117557</td>
<td>± 0.25</td>
</tr>
<tr>
<td>3</td>
<td>0.061803</td>
<td>0.190211</td>
<td>± 0.25</td>
</tr>
<tr>
<td>4</td>
<td>-0.0618</td>
<td>0.190211</td>
<td>± 0.25</td>
</tr>
<tr>
<td>5</td>
<td>-0.1618</td>
<td>0.117557</td>
<td>± 0.25</td>
</tr>
<tr>
<td>6</td>
<td>-0.2</td>
<td>0</td>
<td>± 0.25</td>
</tr>
<tr>
<td>7</td>
<td>-0.1618</td>
<td>-0.11756</td>
<td>± 0.25</td>
</tr>
<tr>
<td>8</td>
<td>-0.0618</td>
<td>-0.19021</td>
<td>± 0.25</td>
</tr>
<tr>
<td>9</td>
<td>0.061803</td>
<td>-0.19021</td>
<td>± 0.25</td>
</tr>
<tr>
<td>10</td>
<td>0.161803</td>
<td>-0.11756</td>
<td>± 0.25</td>
</tr>
</tbody>
</table>

The first antenna configuration tested was an Acute Angle Antenna Baseline (AAAB). Slightly different antenna positions were used compared to the previous single point verification exercise. The antennas were located at the coordinates shown in Table 5.12.
Table 5.12: AAAB Coordinates

<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>0.25</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Next the test point TDoA’s were calculated and the results verified. After this, various perturbations were applied to the TDoA’s. These perturbations consisted of changing the TDoA’s by:

- Rounding to the nearest 1ps
- Rounding to the nearest 20ps
- Rounding to the nearest 40ps
- Shifting all TDoA’s down by 20ps
- Shifting all TDoA’s up by 20ps

The reason for choosing 20ps and 40ps errors was because the oscilloscope used had a maximum sampling rate of 5GSamp/s per channel. This equated to 200ps between samples, which in turn allowed interpolation to 20ps between points. Therefore the best possible resolution when measuring the TDoA’s was on the order of 20ps.

If the error sensitivity of the antenna system was linear, a 20ps change in time difference of arrival on one antenna would equate to a potential 0.6cm error. When all three TDoA’s are off by 20ps, the error would be on the order of 1cm. However, the likelihood of linear error was low due to the nature of the location equations.
Once the locations of the test points were calculated, including all perturbations, they were examined so that the closest calculated points to the actual test points were filtered out. Then the ESD Event Locator Program was used to plot these points. Figures 5.9a and 5.9b show the graphical results for the two sets of circular test points.

Figure 5.9a: AAAB with Positive Z-Axis-Centered Circular Test Points
Figure 5.9b: AAAB with Negative Z-Axis-Centered Circular Test Points

It is easy to see that the perturbations to the TDoA’s had greater effect on the calculated location as the test points became farther from the antennas. The sensitivity to the changes also seemed to increase as the points moved further ‘behind’ the antenna structure. It is difficult to see in Figure 5.9a, but the test points did not actually reside inside the antenna structure. Therefore for this case only, a third set of test points was created, with the same characteristics as the positive z-axis set, but with a radius of 0.5m instead of 0.2m. The resulting graphical data is shown in Figure 5.9c.
The larger circle of test points in Figure 5.9c exhibited the same behavior as the previous two test points, in that the sensitivity to error increased behind the antenna structure and as distance to the structure increased. Once the locations were plotted, the error was examined in more detail. The distance between the test points and the calculated points were calculated. Figures 5.10a-c show the results.
Figure 5.10a: Distance Error for AAAB Positive Z-Axis 0.2m Radius Test Point Perturbations

Figure 5.10b: Distance Error for AAAB Negative Z-Axis 0.2m Radius Test Point Perturbations
Figure 5.10c: Distance Error for AAAB Positive Z-Axis 0.5m Radius Test Point Perturbations

The error plots clearly show the increase in sensitivity as the test points go behind the antenna structure, with a potential for 14-16cm of error. For the 0.5m radius set of test points, there was even one point where a shift perturbation caused a case where no solution was found. When the test points were closest to the antenna structure, in particular the front side, there was generally 1cm of error, with one point having about 2.5cm of error. Interestingly, even a 1ps rounding perturbation had almost 0.5cm error for the worst case test point in Figure 5.10c.
The next antenna configuration tested was the Orthogonal Antenna Baseline (OAB). The antennas were located at the coordinates shown in Table 5.13. The same test point locations as the AAAB case were used, with the exception of the 0.5m radius configuration. The resulting calculated locations are shown in figures 5.11a-b, and the distance error is shown in figures 5.12a-b.

Table 5.13: OAB Coordinates

<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 5.11a: OAB with Positive Z-Axis-Centered Circular Test Points
Figure 5.11b: OAB with Negative Z-Axis-Centered Circular Test Points

Figure 5.12a: Distance Error for OAB Positive Z-Axis 0.2m Radius Test Point Perturbations
The orthogonal antenna baseline results were similar to those of the acute angle antenna baseline results; the error sensitivity was highest behind and away from the antenna system. The lowest sensitivity to error was within the antenna system. Within the antenna system the error was under 1 cm, and with the positive z-axis points, the error was under 3 cm for all points. When the test points were in the negative z-axis region, the error increased such that there was no solution for a couple points (shifted perturbation case).

The next antenna configuration tested was the Obtuse Angle Antenna Baseline (OAAB). The antennas were located at the coordinates shown in Table 5.14. The

Figure 5.12b: Distance Error for OAB Negative Z-Axis 0.2m Radius Test Point Perturbations
same test point locations as the OAB case were used. The resulting calculated locations are shown in figures 5.13a-b, and the distance error is shown in figures 5.14a-b.

Table 5.14: OAAB Coordinates

<table>
<thead>
<tr>
<th>Antenna</th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>-0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>-0.5</td>
<td>-0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 5.13a: OAAB with Positive Z-Axis-Centered Circular Test Points
Figure 5.13b: OAAB with Negative Z-Axis-Centered Circular Test Points

Figure 5.14a: Distance Error for OAAB Positive Z-Axis 0.2m Radius Test Point Perturbations
The obtuse angle antenna baseline configuration was relatively insensitive to error over both test point sets. The worst error was just over 5cm. For the positive z-axis test point set, the error was under 2cm for all points. However this is potentially misleading, since all points in this case were in front of the antenna system.

Consequently, a third set of test points were used for this case. The third data set was circular, with radius 0.75m, and centered on the positive z-axis at a height of 0.25m. The resulting calculated positions are shown in Figure 5.15, and the error plot is shown in Figure 5.16.
Figure 5.15: OAAB with Positive Z-Axis-Centered Circular Test Points, 0.75m Radius Set
As expected, the error increased dramatically with the larger radius test point set. As the test points extended beyond the antenna system to the rear, several points had either high error or no calculated solution at all. For this case the test points also extended beyond the antenna system to the front, which resulted in increased sensitivity to error as well.

Finally, a Planar Antenna Baseline (PAB) was tested. The antennas were located at the coordinates shown in Table 5.15. The same test point locations as the OAB case were used. The resulting calculated locations are shown in Figure 5.17, and the distance error is shown in Figure 5.18.
Table 5.15: PAB Coordinates

<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>-0.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>-0.5</td>
<td>-0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 5.16: PAB with Positive Z-Axis-Centered Circular Test Points
The results of the planar antenna baseline configuration show that it is very sensitive to perturbations. No solution was found for some test points with just an induced 1ps rounding error. Interestingly, for those test points where the 1ps rounding resulted in no solution, the 20ps induced rounding and shifting errors produced a solution with low error (less than 2cm). The least error occurred when the test points lay between the antenna baselines. The higher perturbation sensitivity for the PAB configuration is expected since there is only a 2-D sensing grid of antennas.

Based on the above results, several initial conclusions were drawn. The PAB configuration was the worst performing of the four. Therefore it should be avoided if
possible. For the remaining three configurations, error sensitivity was minimized when the test points were encompassed within the volume defined by the antennas. When the test points were inside the antenna volume, worst-case error for the defined perturbations was approximately 1cm or less. The AAAB configuration was slightly better than the OAB configuration, which in turn was slightly better than the OAAB configuration. For ease of use when placing the antennas, the OAB configuration would be preferred, and would lend itself to easy creation of a fixture to hold the antennas in a known location relative to the first antenna.

Once the various sample antenna configurations were studied for test point error sensitivity, the preferred configuration was studied for antenna placement error sensitivity. In other words, how much error was introduced in the location calculations when the actual antenna locations were different from expected?

Without a fixture placing the antennas in a known location, there would be inevitable placement errors. These errors most likely would be on the order of a few centimeters. In order to see the impact of this, a grid of test points were created. A set of TDoA’s were created for each point for the antennas in the orthogonal configuration. The antennas were on the axes at 0.5m separation. The ESD event locator program then used this information to find the correct locations.

Next, the antenna positions were changed and new TDoA’s were calculated. The resulting TDoA’s were fed into the program, but without updating the antenna
locations in the program. This simulated the case were the antennas were actually at 0.55m separation, for instance, but the user thought they were at 0.5m separation.

Figure 5.18 shows the antenna location perturbations that were used. The antennas were moved in 0.05m increments. Only the fourth antenna was moved off its main axis.

![Figure 5.18: Antenna Locations for Antenna Sensitivity Study](image)

For each set of TDoA’s, the distance from the actual test point location to the closest calculated location was recorded. Once all the data was collected from each set of TDoA’s, distance error for each case was averaged together. Figures 5.19a-g show surface plots of the constant-z slices of this error. The legend indicates average location error in meters.
Figure 5.19a: Sensitivity to Antenna Placement Error, $z = -0.1m$

Figure 5.19b: Sensitivity to Antenna Placement Error, $z = 0.0m$
Figure 5.19c: Sensitivity to Antenna Placement Error, $z = 0.1m$

Figure 5.19d: Sensitivity to Antenna Placement Error, $z = 0.25m$
Figure 5.19e: Sensitivity to Antenna Placement Error, $z = 0.4m$

Figure 5.19f: Sensitivity to Antenna Placement Error, $z = 0.5m$
Figure 5.19g: Sensitivity to Antenna Placement Error, z = 0.6m

Since the antennas were moved in increments of 0.05m, areas where there is less than 0.05m average error in location indicate low error sensitivity. Areas with greater than 0.05cm average location error indicate areas where the sensitivity approaches a level of unsuitability for the application. Some areas, particularly in the slices above and below the antenna structure, showed no solution at all (infinite error). In fact, some of these areas were so sensitive that a solution was not found even without error introduced other than rounding in the calculated TDoA values. These areas included (0,0,-0.1), (0,-0.1,0), (-0.1, 0,0), (0,0.6,0), and most points that lay on any two axes and were outside the antenna structure.

Based on these results, a guide for placing the antennas was developed. The antennas should be placed in an orthogonal configuration, in as accurate a way as possible.
The preferred method would be with a constructed antenna holder of known dimensions. In order to minimize sensitivity to placement error, the antennas should be located such that they fully envelope the suspected ESD event location. Preferably they would extend beyond the suspected location by about 20%. This ensures low sensitivity, less than a 1:1 relationship between antenna placement error and location error, over the entire area.

5.4 Actual Location of ESD Event in 3-Dimensional Space

Once the preferred antenna locations were determined, the whole system (antennas, oscilloscope, PC, and software) needed to be tested as a unit. However, one more thing remained to include in the program before this could be done. There needed to be an easy method for the end user to calibrate, or ‘zero-out’, the path length delays between the four antennas.

During the antenna investigations, one method was found to calibrate the delays: measure the path delays relative to the first antenna one at a time on a TDR. Two things made this an inconvenient method. The first was that it was laborious and would be difficult for a neophyte user to do. The second was that it did not take into account any path length differences within the scope itself. Therefore a simpler method was developed and added to the software.

A fixture was developed that arranged the antennas in a uniform manner around a central point (Figure 5.20a). Then a metallic (copper) shaft was placed slightly above
the antennas along the central line of the fixture (Figure 5.20b). The metallic shaft was used as a discharge point for an ESD gun. Since it was equidistant from all four antennas, an oscilloscope trace would show any time delays between the antenna paths.

![Antenna Delay Calibration Fixture](image)

**Figure 5.20a: Antenna Delay Calibration Fixture**

![Antenna Delay Calibration Fixture with Metallic Discharge Point](image)

**Figure 5.20b: Antenna Delay Calibration Fixture with Metallic Discharge Point**

The software was modified to present the user with a button to calibrate the delays after setting the oscilloscope in the default mode for detecting an ESD event. Once the oscilloscope is set up, the user measures an ESD event generated by the gun.
discharging to the metallic shaft. If an offset between the channels exists, the calibration button is used. Figure 5.21 shows the results of discharging to the shaft. An intentional difference was introduced in the antenna path length (one antenna had half the length of coaxial cable as the other three antennas). It is easy to see in Figure 5.21 that one antenna has a different (shorter) path length.

![Figure 5.21: Screen Capture of Calibration Discharge](image)

Next the user clicks on the “Calibrate Trace Delays” button, which brings up more buttons. The user can either enter in predetermined delays for each channel, or use the cursors on the oscilloscope to read the delays. After determining the delays, the user sets the offsets on the oscilloscope by clicking the “Set Trace Delays” button. Figure 5.22 shows a screen capture of the software just prior to sending the new path
length offsets to the oscilloscope. Figure 5.23 shows a new discharge after calibration. Notice that there is now little difference between the four channels.

![Screen Capture of Calibration Discharge After Reading Antenna Path Length Delays](image)

**Figure 5.22: Screen Capture of Calibration Discharge After Reading Antenna Path Length Delays**
Once the antenna path lengths were calibrated, the entire system was tested by using the grill lighter spark source. The antennas were taped to a support structure and then their locations measured with a metric ruler using the feed-point of each antenna as the reference. The ESD source was placed within the box formed by the antennas. The resulting locations are stated in Table 5.16.

Table 5.16: Test Bench Antenna and ESD Source Coordinates

<table>
<thead>
<tr>
<th>Antenna</th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>0.49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>0</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>0</td>
<td>0</td>
<td>0.29</td>
</tr>
<tr>
<td>ESD Source</td>
<td>0.30</td>
<td>0.20</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Figure 5.24 shows a picture of the test bench setup. The PC attached to the oscilloscope is not shown.

Figure 5.24: Test Bench Setup

The ESD source was measured eight times. Table 5.17 shows the measured TDoA’s. There was significant variability in some of the measurements. In particular the Antenna 1-3 TDoA had the greatest variation with a 290 ps maximum difference between two readings. The Antenna 1-4 TDoA was next worst with 160 ps maximum difference, and Antenna 1-2 TDoA was best with 50ps. It was particularly interesting that the Antenna 1-3 TDoA switched polarity. This was potentially due to ambiguity in the waveforms that made it difficult to choose the correct place to measure the TDoA.
Table 5.17: Sample ESD Event Detection TDoA’s

<table>
<thead>
<tr>
<th>Run</th>
<th>TDoA 1-2 (ps)</th>
<th>TDoA 1-3 (ps)</th>
<th>TDoA 1-4 (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>-225</td>
<td>85</td>
<td>225</td>
</tr>
<tr>
<td>Run 2</td>
<td>-235</td>
<td>75</td>
<td>225</td>
</tr>
<tr>
<td>Run 3</td>
<td>-235</td>
<td>-205</td>
<td>165</td>
</tr>
<tr>
<td>Run 4</td>
<td>-225</td>
<td>-5</td>
<td>175</td>
</tr>
<tr>
<td>Run 5</td>
<td>-195</td>
<td>-145</td>
<td>65</td>
</tr>
<tr>
<td>Run 6</td>
<td>-245</td>
<td>-205</td>
<td>115</td>
</tr>
<tr>
<td>Run 7</td>
<td>-195</td>
<td>15</td>
<td>215</td>
</tr>
<tr>
<td>Run 8</td>
<td>-245</td>
<td>-75</td>
<td>205</td>
</tr>
</tbody>
</table>

After generating the TDoA’s, they were loaded back into the software to calculate possible locations for the ESD source. Figure 5.25 shows the graphical representation of all four sets of possibilities. Only two sets were within the box formed by the antennas. One possible method to resolve the correct answer from the remaining two locations would be to rotate either the product or the antenna system by ninety degrees and repeat the measurements. However, since the actual location was known, this step was not taken.
Table 5.18 shows the calculated coordinates of the ESD source for the TDoA’s from Table 5.17. The closest sample was 1.9 cm away from the actual location of the ESD source, and the farthest sample was 5.5 cm away. The last entry in Table 5.18 shows the average location: the x-coordinates from all eight runs averaged together, repeated for the y- and z-coordinates. The average location was only 1.3 cm away from the ESD source. This would be close enough in an actual product to locate the probable source.
<table>
<thead>
<tr>
<th></th>
<th>x (meters)</th>
<th>y (meters)</th>
<th>z (meters)</th>
<th>Error (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.286</td>
<td>0.150</td>
<td>0.061</td>
<td>0.055</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.288</td>
<td>0.153</td>
<td>0.060</td>
<td>0.053</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.295</td>
<td>0.237</td>
<td>0.075</td>
<td>0.038</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.288</td>
<td>0.176</td>
<td>0.078</td>
<td>0.026</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.287</td>
<td>0.220</td>
<td>0.119</td>
<td>0.045</td>
</tr>
<tr>
<td>Run 6</td>
<td>0.299</td>
<td>0.239</td>
<td>0.096</td>
<td>0.042</td>
</tr>
<tr>
<td>Run 7</td>
<td>0.282</td>
<td>0.171</td>
<td>0.063</td>
<td>0.038</td>
</tr>
<tr>
<td>Run 8</td>
<td>0.293</td>
<td>0.197</td>
<td>0.062</td>
<td>0.019</td>
</tr>
<tr>
<td>Average Location</td>
<td>0.290</td>
<td>0.193</td>
<td>0.077</td>
<td>0.013</td>
</tr>
</tbody>
</table>

There are several potential sources of variation in the above measurement, some of which have already been briefly discussed. Measurement variations can be due to physical properties of the antenna system (antenna construction and placement, coaxial cable properties, ESD source properties), the instruments used to interface with the antennas (oscilloscope and PC), the environment surrounding the antenna system (possible metallic structures near the system), or the person operating the ESD location system (accurate antenna placement/location measurement, interpretation of measured waveforms). These categories are loosely based upon those expounded upon in a Measurement Systems Analysis reference book produced by the major United States automobile manufacturers [44]. A diagram showing the various sources of variation in the ESD location system is shown in Figure 5.26. The more uncontrolled variations in the system, the more sources of error in determining the ESD source location.
Each of the main sources of variation (Instrumentation, Physical Properties of System, Environment, and Operator) can be broken down into finer levels of detail, and as each individual item is addressed the variability of the whole system should decrease. Some variability sources can have large impacts, but most of them have minimal influence on the overall measurement variability and error.
Instrumentation variability is highly dependent on the oscilloscope chosen to measure the ESD waveforms, as well as the type of antennas used. The biggest variability factor is the analog bandwidth of each oscilloscope channel. The wider the bandwidth of the oscilloscope, the better the TDoA’s can be measured. However, once above a certain bandwidth other factors begin to be more dominant. Channel crosstalk may overwhelm weak signals from one or more antennas if the ESD source is particularly close to one of the antennas. Channel vertical scale can cause TDoA variability. If one channel is at a significantly different level than another, there may be unaccounted-for path length delays (different relay paths are used for different voltage scales). This can be reduced by recalibrating the antenna path lengths.

Environmental variability is usually easy to minimize. Most environmental factors like temperature, humidity, atmospheric pressure have little effect on the measurement system. Metallic structures near the antennas can cause multi-path reflections. However, the first pulse to arrive should always be due to the direct path. Metallic structures within a product will cause more problems. The most problematic environmental issue is the possibility of multiple ESD sources (either from outside the measured product, or from multiple discharges with the product). These can result in inconsistent data. External sources can be eliminated by performing testing in a wide open area or within an RF (radio frequency) shielded room.

The physical properties of the system include both the ESD source and the antennas. Coaxial cable differences can cause variations because of different dielectrics,
different lengths, and different bandwidths. Using the exact same type of cable for each antenna minimizes this source of error. The placement of the antennas obviously can influence the error in the system, and has already been explored. The ESD event itself is one of the greatest sources of variability in the measurements. Every ESD event, even if caused by the same source, is variable. It may have slightly different polarizations each time, and it may not always have the highest emissions occur at the same point in the waveform. There is nothing that can be done to minimize this variation, other than by the experience of the system operator.

The operator of the system can also be a significant source of variability in measuring the TDoA’s for an ESD event. The operator controls the placement of the antennas, which is inaccurately placed (or inaccurate placement measurement) can cause a bias in the TDoA’s. A more rigid antenna placement structure with pre-marked locations would mitigate most of this. The operator’s knowledge of how the system operates can introduce variability issues (for instance being unaware of the calibration of path lengths). Also key in minimizing variability in the measurements is the experience of the operator. An experienced operator can better tell the appropriate place to measure the TDoA’s on each waveform. He can even sometimes tell from the waveforms whether there are multiple ESD events present (one ESD event may have a different ring characteristic than another).
Chapter 6. Conclusions and Further Work

6.1 Conclusions

A complete ESD Location System has been developed consisting of a fast oscilloscope, four detection antennas, and software to interface with the oscilloscope and calculate the location of the ESD sources. This system assists developers of electronic devices in quickly tracking down sources of ESD within their products so that precious time and money is not wasted through brute force methods of ESD mitigation.

Several antennas were investigated for suitability in the system. The best choice was a home-made E-Field antenna with a wide bandwidth and good sensitivity. However any set of antennas with good characteristics can be used. The software that was developed is simple to use with minimal instruction, and additional functionality can be added easily.

In conclusion, the ESD locator system has the following results.

- System accuracy was on the order of 1-2 cm.
- The best antenna was found to be a ‘home-made’ E-Field fat monopole.
- The best configuration of the antennas (optimizing ease of placement and sensitivity to error) was found to be an orthogonal arrangement.
- The measured product should be placed such that it is fully within the box formed by the antennas.
Along with relevant product experience, this system allows an engineer to find a probable ESD event quickly.

6.2 Further Work

In any project, more work can be done to improve on the understanding of the studied phenomena, and improvements can be made to any associated software and hardware. Further work in this thesis should focus on three main areas: a study how an ESD event behaves within a product where metallic structures exist, reduction in the location error, and adding more utility to the ESD location software.

The first area would lead to greater understanding of how the initial ESD pulse is affected by surrounding (and possibly attached) metallic structures. Does the added structure increase the error in locating the ESD source? Does it slow down the edge rate of the pulse such that it limits the resolution of the TDoA results?

The second area of further work (improving accuracy) has many avenues to pursue. Since the items listed in Figure 5.26 are sources of measurement variability (and therefore location error), working to better understand each item may help drive down error. For instance, access to a better oscilloscope may be one large source of increased accuracy.

More accurate placement of the antennas may also prove to be fruitful, either by using 3D positional antenna holders or by using a totally different technique to locate
the antenna positions. One possible technique is to use an ESD source to measure the
distance between each antenna, then place the ESD source at several known locations
and use the resulting TDoA’s to fine-tune the antenna locations.

One other potential method to increase accuracy would be to improve the accuracy of
the waveform interpretation. Rather than rely upon the experience of the user, a filter
algorithm may be developed that automatically determines the TDoA’s based upon
the oscilloscope traces.

Finally, improving the software should be a priority as well. Currently the software
only works with one oscilloscope type. The utility of the program would be greatly
improved by making the equipment interface more general. Also, adding new
functionality such as a waveform filter algorithm, or antenna location routine as
discussed above would be helpful.

6.3 Alternate Uses of Antenna System

There are some alternate uses of the antennas and the ESD location system that could
be useful. It should be a simple matter to adapt the system to locate intermittent, non-
ESD events within a product. For instance, if a high-frequency clock or data signal is
fed onto a poorly designed PCB such that the traces efficiently radiate the signal, this
may cause a radiated emissions failure. If it is on continuously, the ESD location
system may not be helpful. However, if the signals are intermittent, or a distinct
pattern can be discerned, then a set of TDoA’s can be measured and the offending source can be located.

Another alternate use of the antenna system is focused on just the antennas that were developed. These antennas may be used to broadcast a disrupting signal into a product to test its immunity to ESD-like events.
Appendix: MathCAD Sheet

The following information is a series of screenshots of the MathCAD sheet used to calculate the ESD event locations. It is based upon one of the techniques shown in [4]. The C++ program was then directly developed from this sheet.

Hyperbolic Positioning of Electrostatic Discharge

Based on "Simple Solutions for Hyperbolic and Related Position Fixes" by Bertrand Fang

Four Receiver Antennas: A, B, C, and C'

A is at the origin (0,0,0)
B is on the x-axis (b_x, 0, 0)
C is on the xy-plane (c_x, c_y, 0)
C' is arbitrary (c'_x, c'_y, c'_z)

Let $T_{ab} = T_a - T_b$, $T_{ac} = T_a - T_c$, and $T_{ac'} = T_a - T_c'$ be the Time Difference of Arrival (TDoA) of a signal to the respective receive antennas.

Let $R_{ab} = \text{(speed of light)}(TDoA) = \text{difference in path length from the source (ESD) to antenna A and antenna B.}$

Let $g, g', h, h', d, d', e, e', f,$ and $f'$ be defined as coefficients in the ESD Location Equation, $R, R'$:

$R = x^i + (g^x + h^x)j + k/\sqrt{[d^x + e^x + f]^2}k$

$R' = x'^i + (g'^x + h'^x)j'/\sqrt{[d'^x + e'^x + f']^2}k'$

Let jjprime and kjprime be the dot product of the two coordinate systems.

Let $p, q,$ and $r$ be coefficients in the dot product of $R$ and $R'$.

$c_{\text{light}} := 2.99792 \times 10^8 \text{ m/s}$

Define ESD Source Location for Testing Purposes, $S(x, y, z)$

$S_x := 0.2 \text{ m} \quad S_y := 0.3 \text{ m} \quad S_z := 0.4 \text{ m}$
Define Antenna Locations

\[ b := 1\text{m} \quad c_x := -1\text{m} \quad c_{\text{prime\_actual\_x}} := -0.5\text{m} \]
\[ c_y := 1\text{m} \quad c_{\text{prime\_actual\_y}} := -0.5\text{m} \]
\[ c_{\text{prime\_actual\_z}} := 1\text{m} \]
\[ c := \sqrt{c_x^2 + c_y^2} \]
\[ c_{\text{prime}} := \sqrt{c_{\text{prime\_actual\_x}}^2 + c_{\text{prime\_actual\_y}}^2 + c_{\text{prime\_actual\_z}}^2} \]
\[ c = 1.414\text{m} \]
\[ c_{\text{prime}} := \sqrt{c_{\text{prime\_actual\_x}}^2 + c_{\text{prime\_actual\_y}}^2 + c_{\text{prime\_actual\_z}}^2} \]
\[ c_{\text{prime}} = 1.225\text{m} \]

Calculate Distances from ESD Source to Antennas and Calculate Sample TDoA's

\[ S_{A\_\text{bar}} := \sqrt{(S_x - 0)^2 + (S_y - 0)^2 + (S_z - 0)^2} \quad S_{A\_\text{bar}} = 0.539\text{m} \]
\[ S_{B\_\text{bar}} := \sqrt{(S_x - b)^2 + (S_y - 0)^2 + (S_z - 0)^2} \quad S_{B\_\text{bar}} = 0.943\text{m} \]
\[ S_{C\_\text{bar}} := \sqrt{(S_x - c_x)^2 + (S_y - c_y)^2 + (S_z - 0)^2} \quad S_{C\_\text{bar}} = 1.446\text{m} \]
\[ S_{C\_\text{prime\_bar}} := \sqrt{(S_x - c_{\text{prime\_actual\_x}})^2 + (S_y - c_{\text{prime\_actual\_y}})^2 + (S_z - c_{\text{prime\_actual\_z}})^2} \]
\[ S_{C\_\text{prime\_bar}} = 1.221\text{m} \]

\[ T_a := \frac{S_{A\_\text{bar}}}{c_{\text{light}}} \quad T_b := \frac{S_{B\_\text{bar}}}{c_{\text{light}}} \quad T_c := \frac{S_{C\_\text{bar}}}{c_{\text{light}}} \quad T_{c\_\text{prime}} := \frac{S_{C\_\text{prime\_bar}}}{c_{\text{light}}} \]
\[ T_{a\_b} := T_a - T_b \quad T_{a\_c} := T_a - T_c \quad T_{a\_c\_\text{prime}} := T_a - T_{c\_\text{prime}} \]
\[ T_{a\_b} = -1.351 \times 10^{-9}\text{s} \quad T_{a\_c} = -3.026 \times 10^{-9}\text{s} \quad T_{a\_c\_\text{prime}} = -2.275 \times 10^{-9}\text{s} \]
Calculate Path Length Differences. Insert Actual TDoA's Here for Experimental Measurements

\[ R_{ab} = c_{\text{light}} T_{ab} \quad R_{ac} = c_{\text{light}} T_{ac} \quad R_{ac\_prime} = c_{\text{light}} T_{ac\_prime} \]

\[ R_{ab} = -0.405 \text{ m} \quad R_{ac} = -0.907 \text{ m} \quad R_{ac\_prime} = -0.682 \text{ m} \]

Calculate \( g, g', h, \) and \( h' \)

\[ g := \left( \frac{1}{c_y} \right) \left[ R_{ac} \left( \frac{b}{R_{ab}} \right) - c_x \right] \]

\[ g = 3.241 \]

\[ g' := \left( \frac{1}{c_{prime\_z}} \right) \left[ R_{ac\_prime} \left( \frac{b}{R_{ab}} \right) - c_{prime\_x} \right] \]

\[ g' = 1.954 \]

\[ h := \frac{c^2 - R_{ac}^2 + R_{ac} R_{ab} \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right]}{2 c_y} \]

\[ h = -0.348 \text{ m} \]

\[ h'_{prime} := \frac{c_{prime}^2 - R_{ac\_prime}^2 + R_{ac\_prime} R_{ab} \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right]}{2 c_{prime\_z}} \]

\[ h'_{prime} = -0.167 \text{ m} \]
Calculate \( d, d', e, e', f, \) and \( f' \)

\[
d := -1 \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 + \varepsilon^2 \right] \quad \quad \quad \quad \quad \quad d' := -1 \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 + \varepsilon_{\text{prime}}^2 \right]
\]

\[
e := b \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right] - 2 \cdot \varepsilon \cdot h \quad \quad \quad \quad \quad \quad e' := b \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right] - 2 \cdot \varepsilon_{\text{prime}} \cdot h_{\text{prime}}
\]

\[
f := \left( \frac{R_{ab}}{4} \right) \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right]^2 - h^2 \quad \quad \quad \quad \quad \quad f' := \left( \frac{R_{ab}}{4} \right) \left[ 1 - \left( \frac{b}{R_{ab}} \right)^2 \right]^2 - h_{\text{prime}}^2
\]

\[
d = -5.401 \quad \quad \quad \quad \quad \quad d' = 1.282
\]

\[
e = -2.844 m \quad \quad \quad \quad \quad \quad e' = -4.447 m
\]

\[
f = 0.945 m^2 \quad \quad \quad \quad \quad \quad f' = 1.038 m^2
\]

Calculate \( j'^*j' \) and \( k'^*j' \)

\[
jj_{\text{prime}} := \frac{c_{\text{prime actual y}}}{\sqrt{c_{\text{prime actual y}}^2 + c_{\text{prime actual z}}^2}} \quad \quad \quad \quad \quad \quad jj_{\text{prime}} = -0.447
\]

\[
kj_{\text{prime}} := \frac{c_{\text{prime actual z}}}{\sqrt{c_{\text{prime actual y}}^2 + c_{\text{prime actual z}}^2}} \quad \quad \quad \quad \quad \quad kj_{\text{prime}} = 0.894
\]

Calculate \( p, q, \) and \( r \)

\[
p := d \cdot (kj_{\text{prime}})^2 - \left( g_{\text{prime}} - g \cdot (jj_{\text{prime}}) \right)^2
\]

\[
q := e \cdot (kj_{\text{prime}})^2 - 2 \left[ g_{\text{prime}} - g \cdot (jj_{\text{prime}}) \right] \left[ h_{\text{prime}} - h \cdot (jj_{\text{prime}}) \right]
\]

\[
r := f \cdot (kj_{\text{prime}})^2 - \left[ h_{\text{prime}} - h \cdot (jj_{\text{prime}}) \right]^2
\]

\[
p = -15.904 \quad \quad \quad \quad \quad \quad q = -0.077 m \quad \quad \quad \quad \quad \quad r = 0.652 m^2
\]
Solve for ESD Location, Four Possibilities

\[
x_{\text{pos}} := \frac{-q + \sqrt{q^2 - 4 \cdot p \cdot r}}{2 \cdot p}
\]

\[
x_{\text{neg}} := \frac{-q - \sqrt{q^2 - 4 \cdot p \cdot r}}{2 \cdot p}
\]

\[
y_{\text{pos}} := g \cdot x_{\text{pos}} + h
\]

\[
y_{\text{neg}} := g \cdot x_{\text{neg}} + h
\]

\[
z_{\text{pospos}} := \sqrt{d \cdot x_{\text{pos}}^2 + e \cdot x_{\text{pos}} + f}
\]

\[
z_{\text{negpos}} := \sqrt{d \cdot x_{\text{neg}}^2 + e \cdot x_{\text{neg}} + f}
\]

\[
z_{\text{posneg}} := -\sqrt{d \cdot x_{\text{pos}}^2 + e \cdot x_{\text{pos}} + f}
\]

\[
z_{\text{negneg}} := -\sqrt{d \cdot x_{\text{neg}}^2 + e \cdot x_{\text{neg}} + f}
\]

1st Potential Location

\[x_{\text{pos}} = -0.205 \text{ m} \quad y_{\text{pos}} = -1.012 \text{ m} \quad z_{\text{pospos}} = 1.141 \text{ m}\]

2nd Potential Location

\[x_{\text{pos}} = -0.205 \text{ m} \quad y_{\text{pos}} = -1.012 \text{ m} \quad z_{\text{posneg}} = -1.141 \text{ m}\]

3rd Potential Location

\[x_{\text{neg}} = 0.2 \text{ m} \quad y_{\text{neg}} = 0.3 \text{ m} \quad z_{\text{negpos}} = 0.4 \text{ m}\]

4th Potential Location

\[x_{\text{neg}} = 0.2 \text{ m} \quad y_{\text{neg}} = 0.3 \text{ m} \quad z_{\text{negneg}} = -0.4 \text{ m}\]

Test Location (if used)

\[S_x = 0.2 \text{ m} \quad S_y = 0.3 \text{ m} \quad S_z = 0.4 \text{ m}\]
Bibliography


VITA

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Prior Publications:

- Hardin et al., "Method and Apparatus for Providing Multiple Spread Spectrum Clock Generator Circuits with Overlapping Output Frequencies", United States Patent #6,658,043.

Signed: Robert A. Oglesbee Date: December 4th, 2007