Final Report

AM Frequency Electrical Noise Location System

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Executive Summary

An electrical noise location system determines the angle of arrival of electrical noise transmissions. Such a system can be used to minimize noise reception for noise sensitive applications by placing them away from the located noise sources. In general, a noise location system’s requires a radio receiver that operates in the same frequency band and a method to determine and output the angle of arrival of the received noise.

The Q-Track Corporation, which markets a system called the QT-400, has asked that an electrical noise location system be designed to operate in the AM frequency band. The QT-400 is a real-time location system that can track multiple targets within GPS denied areas like indoors. Currently, electrical noise inhibits the QT-400’s performance, especially since it is expected to operate in noisy indoor environments, and an electrical noise location system would be a useful benefit.

Specifically, the design is implemented using the QT-400 radio receiver. Q-Track provided software to interface with its hardware in the C# programming language. An angle of arrival algorithm and GUI shell was then developed and implemented on top of the existing software provided. The algorithm uses both amplitude and phase comparison to calculate the angle of arrival of incident RF. The GUI provides a means for the user to communicate with the QT-400 and view RF spectrum data.

The system’s development cost a total of $16,196, most of which went towards labor. Only $68 worth of additional hardware was necessary to complete the design. The system measures the angle of arrival of AM broadcast stations to within the specifications set out in the proposal, but it is not currently successful in measuring the angle of arrival of test noise source transmitters.
AM Frequency Electrical Noise Location System Using QT-400

The Q-Track Corporation, which is developing a system called the QT-400 to be used as a real-time location system (RTLS), requested that an electrical noise location system be built as an add-on to its system. They hope that detecting electrical noise can improve the performance of the QT-400.

1. Introduction

1.1 Objective

The QT-400 is a RTLS that operates in the AM frequency band (530 kHz to 1710 kHz). It has the capability to track numerous targets using active tags and a number of locator-receivers placed throughout a tracking area. Its performance is dependent on the amount of electrical noise in the tracking area. Specifically, strong noise sources near the QT-400 locator-receivers decrease the signal to noise ratio of the RF system, making the data received less reliable. With the capability to identify where noise sources are with respect to the locator-receivers using the QT-400, Q-Track could optimize its system’s performance by reducing the noise received.

1.2 Motivation

The Global Positioning System (GPS) is an accurate, cost-effective RTLS in many environments. GPS is not practical in noisy and lossy environments, especially indoors, because of its weak signal; the QT-400, which uses a technique known as Near-Field Electromagnetic Ranging (NFER), is designed to be used in GPS denied areas. NFER has many advantages to GPS in certain environments. One such advantage is its lower operating frequency, but it is still limited by noise. Q-Track has found that placing the locator-receivers in some places results in less received noise than other positions, and through trial and error acceptable locations for the locator-receivers are found. However, if Q-Track could locate strong noise sources and position the locator-receivers with noise in mind, the QT-400’s tracking capabilities would be enhanced.
Of course, the electrical noise location system does not solely have one application; many other groups would probably be interested in a similar system. People testing electronics in a lab might want to identify and neutralize noise sources so the noise does not interfere with their tests. Groups enforcing frequency band usage, like the FCC and broadcast AM radio stations, might want to locate offending electronic equipment or rogue transmissions, a task with which this system could help. Those receiving AM broadcasts could also optimize the positioning of their radios using this system by locating and avoiding noise sources. Finally, there are even applications outside noise detection: A system which can locate a fixed transmission like an AM broadcast station relative to itself could feasibly be used as a RTLS within the particular AM station’s range.

1.3 Background

1.3.1 Direction Finding Techniques

Several popular methods are currently used for direction finding of radio signals. Most of these methods involve using a receiver system of three or more antennas to receive the radio wave and process the relative difference in either the wave’s phase or amplitude to determine its angle of arrival. The output is usually displayed in the form of a compass location or simply an arrow pointing in the direction of the source [1].

Techniques for amplitude-comparison utilize the fact that the amplitude difference between two antennas of a single incident radio signal will be unique for every angle of arrival of in a 180-degree semi-circle. A third sense antenna distinguishes on which side of the plane formed by the two antennas the wave is incident, giving the receiver a range of 360 degrees. Among the widely used receiver systems employing amplitude-comparison are the Watson-Watt technique, which uses an Adcock antenna array, and the Wullenweber system [2].
Phase-comparison direction finding setups use a three-antenna array. A radio wave incident on the array will have a unique phase difference between the three antennas depending on its angle of arrival. Most of the commercially available phase-comparison systems use a pseudo-Doppler technique to calculate the wave’s direction [2].

1.3.2 The QT-400

Multiple arrays of direction finding systems can be combined to form a RTLS. Alternatively, Q-Track uses a unique technique it calls NFER, which takes advantage of the fact that close to a transmitting antenna, there is a phase difference of 90° between the electric and magnetic fields of the transmitted electromagnetic wave and that the phase difference goes to 0° as the range from the antenna increases [3], [4]. Consisting of one or more transmitters and a number of locator-receivers strategically located around a tracking area, the QT-400 is Q-Track’s latest system utilizing this technology. The QT-400 operates in select frequencies in the AM broadcast band, from 530 kHz to 1710 kHz; the locator-receiver has a bandwidth of 400 Hz [5].

A picture of one of the locator-receiver boxes appears in Figure 1a below, and the completed setup with its antennas appears in Figure 1b.

Figure 1a (Left). QT-400 Locator-Receiver Box [5].
Figure 1b (Right). QT-400 Locator-Receiver with Antennas [5].
The 2 loop antennas in Figure 1b (the white PVC pipes) connect to channels A and C on the QT-400 locator-receiver box. An electric whip antenna connects to channel B. The two loop antennas receive the magnetic field, and the electric whip antenna receives the electric field, allowing the phase to be measured and the range computed.

Note the presence of the Compact Flash 802.11b card in the locator-receiver. The QT-400 connects via 802.11b to a wireless router, which in turn connects to a PC. Q-Track has a software application that then converts the 802.11b packets which the receiver outputs to usable data. It also has a tracking program which outputs an \((x, y)\) coordinate; this capability is not used in the electrical noise location system.

2. Project Description and Goals

The electrical noise location system satisfies the following goals:

- Detects radio signals in the AM frequency band,
- Sends signal information from the receiver to a computer,
- Calculates and displays in a graphical-user interface the angle of arrival of received radio waves with a user-defined frequency, and
- Sweeps through user-defined start, stop, and step frequencies and displays in the same GUI named above the resulting spectrum data in a waterfall plot.

It was desired that the system developed be compatible with the QT-400 to allow Q-Track to easily use it without any significant infrastructure costs. Therefore, the radio signals are measured using a QT-400 locator-receiver provided by Q-Track. The locator-receiver reports signal data to a computer through a wireless network, and the computer implements the actual processing and direction finding. A GUI displays a graph of the signal strength for user-defined frequencies within the AM band and the angle of arrival of signals at a user-defined frequency.
Using this application, the user can view the spectrum plot to identify the frequency of unwanted signals (i.e., noise), then input that frequency to determine the signals’ angle of arrival.

The system’s accuracy was tested using a noise transmitter that was designed and constructed. The basic transmitter amplifies a signal from a function or signal generator and transmits it via a short whip antenna. The frequency of the function generator’s output can be adjusted to adjust the output frequency of the noise source. Note that this source simply transmits a sine wave with the desired frequency. That is, it does not transmit broadband noise across a broad spectrum.

3. Technical Specifications

A list of the system’s technical specification is shown in Table 1 below.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Target Value</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>530 kHz – 1710 kHz (AM band)</td>
<td>530 kHz – 1710 kHz</td>
</tr>
<tr>
<td>User-defined frequency for angle of arrival calculation</td>
<td>Software feature</td>
<td>Met</td>
</tr>
<tr>
<td>Accuracy of angle of arrival</td>
<td>±15°</td>
<td>±10°</td>
</tr>
<tr>
<td>User-defined frequency range for plotting</td>
<td>Software feature</td>
<td>Met</td>
</tr>
<tr>
<td>User-defined frequency step size for plotting</td>
<td>Software feature</td>
<td>Met</td>
</tr>
<tr>
<td>User-defined sweep time in frequency range</td>
<td>Software feature</td>
<td>Not met</td>
</tr>
<tr>
<td>User-defined refresh rate of graph</td>
<td>Software feature</td>
<td>Met</td>
</tr>
<tr>
<td>Noise source power dissipated in final transistor</td>
<td>Not to exceed 100 mW (+20 dBm)</td>
<td>Met</td>
</tr>
<tr>
<td>Length of feedline and antenna in noise source</td>
<td>Not to exceed 10 feet</td>
<td>3 feet</td>
</tr>
<tr>
<td>Noise source amplifier gain</td>
<td>20 dB</td>
<td>Roughly 20 dB</td>
</tr>
<tr>
<td>Size of system</td>
<td>TBD</td>
<td>QT-400 size</td>
</tr>
<tr>
<td>Size of noise sources</td>
<td>TBD</td>
<td>Breadboard</td>
</tr>
<tr>
<td>Range of noise detection</td>
<td>TBD</td>
<td>Depends on power</td>
</tr>
</tbody>
</table>

The angle of arrival of a broadcast AM radio station was measured accurately to within 10° on average, which meets the proposed specification of ±15°. However, the same success...
was not seen using the test noise sources that were built; the algorithm was not accurate at all in calculating the angle of arrival of these signals.

At the outset of development, the goals for the GUI included allowing the user to set the following fields:

1. The frequency of the noise source whose angle of arrival is to be determined
   (Specification: User-defined frequency for angle of arrival calculation),
2. Frequencies at which spectral data is to be plotted (Specification: User-defined frequency range for plotting and user-defined frequency step size for plotting),
3. Time an individual sweep takes (Specification: User-defined sweep time), and
4. How often the graphical display reflects new data (Specification: User-defined refresh rate of graph).

The GUI meets three of the four set goals. The GUI does not allow the user to choose the sweep time because the program to access the QT-400 does not have this capability.

The noise sources met all the specifications set for it.

The remaining specifications were not part of the criteria of the design. The size of the final setup is the same as that of the QT-400; no new hardware was added to the system itself. Used solely as test beds for the system, the noise sources were built on and are the same size as an electronic breadboard. A specification on the range to detect noise sources could not be determined because the range depends too much on the power and frequency of the given transmitter: An AM broadcast station can be received miles away, but other sources can only be received a few feet away.

4. **Design Approach and Details**

4.1 **Design Approach**

The system was built using the following equipment provided by Q-Track:
- QT-400 locator-receiver box
- 2 loop antennas
- 1 electric whip antenna
- Software application that outputs data provided by QT-400

The system was completed with the development of a software application that calculates the location of noise sources and outputs the results to the user in an easy-to-use GUI and a noise source to test the system.

4.1.1 GUI

The software was written in C# to ensure compatibility with Q-Track’s software. Development was done in Visual Studio 2005. The project files are bundled with the documentation on the group’s website.

Data is acquired by an 802.11b wireless link with a wireless router and the QT-400 using a software package provided by Q-Track called the SDKLiteLibrary. Specifically, the SDKLiteLibrary sets the QT-400 to spectrum from a changeable start, stop, and increment frequency. It in turn outputs the current frequency, the received power level on channels A, B, and C, the phase difference between all three channels, and the percentage of locked data of each channel of the QT-400.

The spectrum plot was created using MATLAB functions that were deployed to .NET components using MATLAB release R2007a. The function used to plot channel A is in Appendix A; functions to plot channels B and C are similar. Data is added as it is received by the C# program to the MATLAB function, which in turn saves all of the data collected to a .mat file. The program plots using the MATLAB surf function and saves the plots as .jpg files, which are then displayed on the GUI.

A screenshot of the GUI appears in Figure 2.
At the top is a menu bar that allows the user to adjust the connection options to the QT-400. The user can specify the IP address of the QT-400, the QT-400 receive port, and the QT-400 transmit port. Typically, the IP address is in the form 192.168.101.1XX, where XX is specified by Q-Track in the QT-400 firmware, the receive port is 31XX, where XX is the same number as above, and the transmit port is 3000.

Below that is a field that allows the user to specify the Frequency of Interest, or the frequency where the angle of arrival should be calculated. The calculated number will be displayed when the sweep reaches the given frequency. If the signal at the frequency of interest is not strong enough for an accurate angle to be measured, the box will display –1. Clicking Update will update the Frequency of Interest as a sweep is occurring.

Figure 2. GUI Application.
Next, there are fields that allow the user to specify the start, stop, and step frequencies of the sweep and the graphs’ refresh rates. Alternatively, the user can immediately view a graph of the data by clicking on the Display Graph button. Graphs will still be displayed after every refresh rate when this button is pressed.

The user can begin and end frequency sweeps using the Start and Stop buttons at the bottom. Once a sweep is begun, its frequency parameters cannot be changed, and their text boxes will freeze. To begin a new sweep, the user can click Stop and change the parameters before hitting Start again. As a sweep progresses, a status bar specifies the current frequency being read, and a progress bar shows the current position in the sweep.

4.1.2 Angle of Arrival Algorithm

The angle of arrival of radio signals is calculated using a network of 2 orthogonal magnetic loop antennas and an electric whip antenna using the following algorithm. For a discussion on the theory behind the algorithm, see Appendix B.

See Figure 3 below for a flow chart of the algorithm’s process.
First, the algorithm checks to make sure that all three channels of the QT-400 are locked. The QT-400 has a phase-locked loop that locks onto strong input waveforms. The

**Figure 3.** Flow chart of the angle of arrival.
SDKLiteLibrary reports the percentage of data in a sample that is locked, and a percentage greater than 75% is considered a locked sample. If the data is not locked, the phase data will be unreliable, and the algorithm will not work, so a –1 is displayed to the user.

Assuming the data is locked, the angle of arrival is calculated first by converting the received powers of the magnetic loop antennas to field strengths. The received power is given in dBm, which is related to the power in Watts according to:

\[
P_{\text{dBm}} = 10 \log \left( \frac{P_W}{0.001} \right)
\]

(Eq. 1)

Solving for \(P_W\) gives:

\[
P_W = 0.001 \cdot 10^{P_{\text{dBm}}/10}
\]

(Eq. 2)

Using the fact that

\[
P_W = \frac{V^2}{R_A}
\]

(Eq. 3)

where \(P_W\) is power in W, \(V\) is the voltage at the antenna, and \(R_A\) is the antenna impedance, one can write the voltage at the antenna (and therefore the field strength) as:

\[
V = \sqrt{P_W R} = \sqrt{0.001 R \cdot 10^{P_{\text{dBm}}/10}} = \sqrt{0.001 R \cdot 10^{P_{\text{dBm}}/20}}
\]

(Eq. 4)

The angle of arrival is computed using the fundamental angle of arrival \(\theta\) as explained in Appendix B:

\[
\theta = \arctan \left( \frac{V_C}{V_A} \right)
\]

(Eq. 5)

where \(V_C\) is the voltage on antenna C and \(V_A\) is the voltage on channel A. Substituting \(V\) in Eq. 3 into Eq. 4 results in:
\[ \theta = \arctan \left( \frac{\sqrt{0.001R} \cdot 10^{P_{dBm,C} / 20} - \sqrt{0.001R} \cdot 10^{P_{dBm,A} / 20}}{10^{P_{dBm,C} / 20} - P_{dBm,A} / 20} \right) \] (Eq. 6)

Tests determined that adding 7.5 dBm to channel A resulted in a more accurate calculation. Therefore, the fundamental angle of arrival is calculated according to:

\[ \theta = \arctan \left( 10^{P_{dBm,C} / 20 - (P_{dBm,A} + 7.5) / 20} \right) \] (Eq. 7)

To complete the fundamental angle of arrival, make it negative if the phase difference between the two magnetic antennas is about equal (or closer to equal than 180° apart). Note that making it negative is equivalent to taking \( \theta = -\theta + 360° \).

Tests determined that when the phase difference between channel A and channel B is between 35° and 215°, the correct angle of arrival is obtained by adding 90° to the resultant angle from the last step. Otherwise, the correct angle of arrival is the angle minus 90°.

Finally, the angle output is made to fall in the range from 0° to 360°.

The C# method that is used to calculate the angle of arrival with the algorithm explained above is shown in Appendix C.

4.1.3 Noise Sources

The noise sources used to test the radio direction finder consist of three main components:

1. A signal generator to create a sinusoidal signal in the AM frequency band,
2. A MOSFET power amplifier to step up sinusoidal signal, and
3. A radio antenna to transmit amplified signal

A schematic of the power amplifier circuit used is shown in Figure 4.
Resistors R2 and R3 are variable. They set the bias of the MOSFET, thereby adjusting the power consumption. R2 and R3 must be set such that the MOSFET draws less than 100 mW.

4.2 Codes and Standards

The most important code pertaining to the project is the limitations that the FCC puts on unlicensed, homemade transmitting devices. For the frequencies in which our test noise sources operate, the FCC Part 15 rules mandate that the maximum permitted power output is 100 mW. Further, the maximum combined length of the transmission antenna and feedline is 10 ft [6]. This code was easily met; the noise source did not need to transmit more than 100 mW since the distances involved were within the size of a normal room.

The IEEE 802.11b wireless internet (or Wi-Fi) standard also applies to the system. 802.11b is an extension of the 802.11 wireless internet but operates at a frequency of 2.4 GHz and only offers 11 different channels. Adherence to this standard is mandatory since the QT-400
locator-receiver communicates only in this fashion. This restriction added some difficulty and complexity to the design since the hardware could not communicate through physical cables.

4.3 Constraints, Alternatives, and Tradeoffs

Because the noise location system built is meant to be used to better place QT-400 locator-receivers, compatibility with the QT-400 system was a major constraint on the design. The hardware was constrained to the QT-400, and software was written in C# to ensure compatibility with other Q-Track software.

Numerous alternatives exist for direction finding radio signals. Some of them are discussed in the Background section of the Introduction, and they include both amplitude comparison and phase comparison techniques. The algorithm described above that was developed for Q-Track is a type of amplitude comparison technology. It was chosen primarily because of the constraints and limitations of the hardware; the QT-400 lacks the phase precision necessary for building a phase comparison system.

Moreover, while a different bank of antennas could have been designed and constructed to use a different amplitude comparison technique, it was desirable to use the antennas already provided because their use does not impose a significant burden on Q-Track’s part in using the system. Furthermore, while a different radio could have been developed that would have opened up the number of direction-finding methods possible, it would not have been compatible with the QT-400 and therefore would have incurred significant costs to Q-Track. Even so, the QT-400 by itself is an excellent radio receiver; the cost of rivaling the accuracy the QT-400 provides makes this option less feasible regardless.

Ultimately, there is a trade-off between compatibility with the QT-400 and the number of direction-finding methods available. It was very important that the noise location system be
compatible with the QT-400, and so Q-Track’s needs were best met by developing a system using that product.

5. **Schedule, Tasks, and Milestones**

The main development tasks fell into one of three areas:

4. The GUI application and software, which was Brandon Denney’s responsibility.

5. Programming and testing the algorithm, which was Andrew Compston’s responsibility.

6. Designing and building test noise sources, which was Josh Gordon’s responsibility.

See Figure 5 for a Gantt chart showing the planned design schedule for these areas and the delays that occurred in each.

![Figure 5. Project schedule.](image)

The development team ran into major problems from the beginning of the design process. Q-Track sent three successive QT-400 kits, all of which were unusable in their initial form, and two were sent back after attempting to debug them here. The development team did not
successfully connect to a QT-400 until 28 November, which is when they had originally planned to be working out the systems’ final bugs. This was a crucial milestone that should have been met by mid-October at the latest. Because of the lengthy delay, there was not sufficient time to fully test the angle of arrival algorithm and the noise transmitters.

Plotting the spectrum data proved more difficult than the development team originally anticipated. This too ran much later than it should have but fortunately was still successful.

6. Project Demonstration

First, the angle of arrival of a broadcast AM radio station was measured using the algorithm. The QT-400 was rotated through all 360°, and the measured angle of arrival was compared to the actual angle. A graph of the actual angle and the measured angle is shown below in Figure 5 for two separate sweeps:

Figure 5. Comparison of the measured angle of arrival vs. actual angle of arrival for a
The sweeps have an average error of 7.98° and 8.92°, respectively.

Next, the angle of arrival was measured for the test noise sources. A graph of the results for one rotation appears in Figure 6 below.

![Figure 6. Measured angle of arrival vs. actual angle of arrival for the test noise source.](image)

Clearly, the algorithm is not accurate for this source. The average error for this sweep is 64.43°.

Additional tests could be done to determine why the angle of arrival of the test noise sources is not accurately measured. The most obvious difference between the broadcast AM radio station and the test source is the distance between each and the QT-400. It may be that the electrical noise location system is not accurate within a certain distance.
Once the inaccuracy of the angle of arrival algorithm using the test noise sources is resolved, another question remaining is whether or not two sources at the same frequency but at different locations will disrupt the angle of arrival calculation. The development team suspects that two sources will cause problems in the algorithm currently being used.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

The Q-Track Corporation has asked that a system be designed and built to be incorporated into its QT-400. This is a one-time development to be compatible only with its equipment, meaning the project has no market outside of the QT-400. Q-Track has already performed a marketing analysis on the QT-400.

7.2 Cost Analysis

Q-Track will provide the necessary hardware and parts for the design. The most significant cost is labor. All of the predicted costs are tabulated as follows.

<table>
<thead>
<tr>
<th>Table 2. Labor Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecture Attendance</td>
</tr>
<tr>
<td>3 hours/week</td>
</tr>
<tr>
<td>x$24/hour</td>
</tr>
<tr>
<td>x16 weeks</td>
</tr>
<tr>
<td>x3 engineers</td>
</tr>
<tr>
<td>Subtotal</td>
</tr>
<tr>
<td>Parts</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

The bulk of the development cost goes to the salaries of the three engineers that worked on the system. The cost for parts comes from the noise sources that were purchased through James Steinberg and Edgar Jones of the Georgia Tech School of ECE.
8. Summary

The electrical noise location system successfully calculates the angle of arrival of some incident electromagnetic waves, and the accompanying GUI meets all of the major goals set out for it by Q-Track. However, the angle of arrival algorithm developed does not accurately calculate angles for the test noise sources that were built to test the system.

Given more time to develop and test the system, the development team would have liked to further explore why the angle of algorithm does not work for the test noise sources. If the numerous problems with connecting to the QT-400 had not been an issue, the development team would have had the time necessary to complete this task. In order to maximize the time available to test the system, the team should have focused on the initial schedule set out in the proposal and completed other tasks that did not require connecting to the QT-400, like developing the GUI. Instead, valuable time was wasted on such endeavors when the connection was established.

Regardless, the electrical noise location system still has a number of feasible applications, including many of those discussed in the Introduction, because of its ability to verifiably calculate the angle of arrival of broadcast AM radio stations. With more testing, the development team might also be able to determine exactly what kind of signal is required for the angle of arrival algorithm to work.
9. References


Appendix A; MATLAB Plotting Program

```matlab
function status = qtplota(bool_firsttime, bool_plot, double_cmax, ...
    double_rssimin, int_frequency, double_rssiA, int_startfrequency, ...
    int_stepfrequency, int_stopfrequency)

% STATUS = QTPLOTA(BOOL_FIRSTTIME, BOOL_PLOT, DOUBLE_CMAX, DOUBLE_RSSIMIN,
%    INT_FREQUENCY, DOUBLE_RSSIA, INT_STARTFREQUENCY INT_STEPFREQUENCY,
%    INT_STOPFREQUENCY)
%
% Plots channel A data for the QT-400 noise location system. Data can be
% added one at a time, and when the data is added, it can be plotted.
% %
% Inputs:
% - BOOL_FIRSTTIME: True if this is the first time running the function
%   (or if you want to clear the data)
% - BOOL_PLOT: True if you want to plot the data
% - DOUBLE_CMAX: Maximum color for the colorbar (a good number is -75)
% - DOUBLE_RSSIMIN: Minimum color for colorbar (make it less than any
%   possible number because bad data will be set to this; a good number is
%   -135)
% - INT_FREQUENCY: Current frequency of the data to add
% - DOUBLE_RSSIA: RSSI A data to add
% - INT_STARTFREQUENCY: Starting frequency in increment
% - INT_STOPFREQUENCY: Stopping frequency in increment
% - INT_STEPFREQUENCY: Frequency increment
%
% Outputs:
% - STATUS: 1 if the function graphed, -1 if it did not

axis_size = 12;
title_size = 16;

% Add data to new variables if this is the first time calling the function
if bool_firsttime
    frequency = int_startfrequency / 1000 : int_stepfrequency / 1000 : ...
        int_stopfrequency / 1000;
    last_frequency = int_frequency;
    rssiA = double_rssiA;
    sweep = 1;
    save qtplota.mat frequency last_frequency sweep rssiA;
end

% Assume the function will not graph
status = -1;

load qtplota.mat

% Only graph if asked and if there is enough data
if bool_plot && length(frequency) > 1 && length(sweep) > 2
    % If the current sweep is not completed, use data up to the last sweep
    if length(rssiA) ~= length(frequency)*length(sweep)
        sweep = sweep(1 : end - 1);
    end
end
```

Group6 (ECE4007L02)
% Form data into a matrix
rssiA = reshape(rssiA(1 : length(frequency)*length(sweep)), ...
    length(frequency), length(sweep));

surf(sweep, frequency, rssiA);

% Makes the black lines in a surface plot go away (for ease of viewing)
shading flat

% Put title on graph
title('Channel A Spectrum', 'FontSize', title_size);

% Label axes
xlabel('Sweep (most recent bottom)', 'FontSize', axis_size);
ylabel('Frequency (in kHz)', 'FontSize', axis_size);
set(gca, 'FontSize', axis_size);
axis([1 sweep(end) frequency(1) frequency(end)]);

% Set the colormap details
cmap = colormap; % Gets the default colormap
cmap(1, :) = [0 0 0]; % Makes the smallest value (lost data) black
colormap(cmap); % Sets the current colormap to cmap

% Set the colorbar
caxis([double_rssimin double_cmax]); % Keeps the colorbar consistent
colorbar('FontSize', axis_size);

grid on;
view([90 90])

saveas(gcf, 'qtplota.jpg')
close

status = 1;

elseif ~bool_firsttime && ~bool_plot

% Start with the assumption that no data was skipped
skipped = 0;

% If the frequency is not what you expect, data may have been skipped
if int_frequency ~= last_frequency + int_stepfrequency
    % If the current frequency is less than the last frequency, the sweep was reset, so increment sweep and check for skipped data
    if int_frequency < last_frequency
        skipped = (frequency(end) * 1000 - last_frequency + ...
            int_frequency - frequency(1) * 1000) / int_stepfrequency;
    % Otherwise, data was skipped
    else
        skipped = (int_frequency - last_frequency) / ...
            int_stepfrequency - 1;
% Add the current value to RSSIA with rssi_min in any skipped elements
rssiA(end + 1 : end + 1 + skipped) = [double_rssimin * ...
ones(1, skipped), double_rssiA];

last_frequency = int_frequency;
save qtplota.mat frequency last_frequency sweep rssiA;

end
Appendix B: Theoretical Discussion on Angle of Arrival Algorithm

The QT-400 has 2 orthogonal, electrically small magnetic loop antennas and an omnidirectional, electrically small electric whip antenna.

Each loop antenna has a null pointing along its axis and a maximum 90° from this. As the 2 loop antennas are orthogonal to each other, the pattern function of the two loops in the horizontal plane is given by:

\[ P_1(\theta = 90^\circ, \phi) = \sin^2 \phi, \text{ loop 1} \]
\[ P_2(\theta = 90^\circ, \phi) = \cos^2 \phi, \text{ loop 2} \]  

(Eq. B1)

Graphically, this is shown in Figure B1.

![Loop antenna patterns](image)

**Figure B1.** Loop antenna patterns.

The complex voltage on each loop can be represented as:
\[ \tilde{A}_1 = A_1 e^{j\phi_1} \]
\[ \tilde{A}_2 = A_2 e^{j\phi_2} \]  

such that:

\[ V_1(t) = \text{Re}(\tilde{A}_1 e^{j\alpha}) \]  
\[ V_2(t) = \text{Re}(\tilde{A}_2 e^{j\alpha}) \]  

One can create a virtual loop oriented in any direction \( \alpha \) by combining the two channels’ voltages in a weighted sum according to:

\[ V_{\text{virtual}}(\theta, t) = V_1(t) \cos \theta + V_2(t) \sin \theta \]  

This can also be represented in the complex domain as:

\[
V_{\text{virtual}}(\theta, t) = \text{Re}(A_1 e^{j\phi_1} e^{j\alpha} \cos \theta + A_2 e^{j\phi_2} e^{j\alpha} \sin \theta)
\]

\[
= \text{Re}\left( A_1 (\cos \phi_1 + j \sin \phi_1) \cos \theta + A_2 (\cos \phi_2 + j \sin \phi_2) \sin \theta \right) e^{j\alpha}
\]

\[
= \text{Re}\left( A_1 \cos \phi_1 \cos \theta + A_2 \cos \phi_2 \sin \theta + j(A_1 \sin \phi_1 \cos \theta + A_2 \sin \phi_2 \sin \theta) \right) e^{j\alpha}
\]  

The magnitude of the virtual loop, then, is:

\[
|\tilde{A}_{\text{virtual}}(\theta)| = \sqrt{(A_1 \cos \phi_1 \cos \theta + A_2 \cos \phi_2 \sin \theta)^2 + (A_1 \sin \phi_1 \cos \theta + A_2 \sin \phi_2 \sin \theta)^2}
\]  

Expanding this and using the trigonometric identity \( \cos(\theta - \phi) = \cos \theta \cos \phi + \sin \theta \sin \phi \) results in:
There is a $180^\circ$ phase flip across the two lobes of the electrically small loop antenna. That means that the phase difference between the two loops can theoretically take only one of two values: $0^\circ$ or $180^\circ$. Using this fact results in the following for the magnitude:

\[
|\mathbf{\tilde{A}}_{\text{virtual}}(\theta)| = \begin{cases} 
\sqrt{A_1^2 \cos^2 \theta + A_2^2 \sin^2 \theta} 
+ 2A_1A_2 \cos \psi \sin \theta 
, |\phi_1 - \phi_2| = 0^\circ \\
\sqrt{A_1^2 \cos^2 \theta + A_2^2 \sin^2 \theta} 
- 2A_1A_2 \cos \psi \sin \theta 
, |\phi_1 - \phi_2| = 180^\circ 
\end{cases} 
\]

(Eq. B8)

The two cases represent the fact that there is a front-back ambiguity in the virtual loop. There are two lobes in a loop antenna, so if the signal received is a maximum, one cannot unambiguously say it is coming from one lobe or the other. This ambiguity can be resolved using the electric whip antenna.

Note that the lobe of the virtual loop is measured from loop 1. That is, the maximum of the virtual loop is at an angle $\theta$ measured from the maximum of loop 1. Finding the angle $\theta$ that minimizes the magnitude of the virtual loop and then adding or subtracting $90^\circ$ to this fundamental angle will result in an angle of arrival measurement measured from the maximum of
lobe 1 (which lobe depending on the choice of adding or subtracting 90°). Therefore, calculate the fundamental angle of arrival by setting the magnitude to its minimum value, 0:

\[
\theta = \begin{cases} 
-\arctan\left(\frac{A_1}{A_2}\right), & |\phi_1 - \phi_2| = 0^\circ \\
\arctan\left(\frac{A_1}{A_2}\right), & |\phi_1 - \phi_2| = 180^\circ 
\end{cases}
\]

(Eq. B9)

There is also a 180° phase flip across the two lobes of the virtual loop. This fact can be utilized to resolve the front-back ambiguity by combing the virtual loop response with the omnidirectional electric whip antenna response. The two voltages will constructively add for one lobe of the virtual loop and destructively add for the other. This forms a cardiod pattern that is unidirectional; that is, it has one maximum.

Practically, combining the electric and magnetic responses using the QT-400 is not possible because the phase of the electric field cannot be measured. However, by determining what phase values between the electric and magnetic fields result in the desired angle of arrival, one can resolve this ambiguity.
Appendix C: C# Method calc_angle

/*
 * Calculates the angle of arrival of the incident RF signal.
 */
private double calc_angle(double RSSIA_dBm, double RSSIC_dBm, double PhaseAB,
 double PhaseAC, float lockA, float lockB, float lockC)
{
    // Only calculate the angle if the data is locked (return -1 otherwise)
    if (lockA > 0.75 && lockB > 0.75 && lockC > 0.75)
    {
        // Calculate the angle of arrival as: (tests showed more accuracy by
        // adding 7.5 to RSSI_A)
        double angle = Math.Atan(Math.Pow(10, RSSIC_dBm / 20 -
                                   (RSSIA_dBm + 7.5) / 20));

        // Make the angle negative if the magnetic phases are about equal
        // (well, if they are closer to equal than 180 degrees apart)
        if (PhaseAC < 90)
        {
            angle = 2 * Math.PI - angle;
        }

        // Tests determined that if PhaseAB is between 35 and 215, the AoA is
        // angle+pi/2; otherwise, it is angle-pi/2
        if (PhaseAB < 215 && PhaseAB > 35)
        {
            angle += Math.PI / 2;
        }
        else
        {
            angle -= Math.PI / 2;
        }

        /* Make angle fall in the range [0, 2pi) */
        // Make angle positive (keep adding 2pi to it until it is)
        while (angle < 0)
        {
            angle += 2 * Math.PI;
        }

        // Take the modulus of angle with 2pi
        angle = angle % (2 * Math.PI);

        // Return the angle (convert it to degrees)
        return angle * 180.0 / Math.PI;
    }
    else
    {
        return -1;
    }
}