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DEPARTMENT OF ELECTRICAL ENGINEERING

A MODEL OF THE PLASMA FREQUENCY PROBE

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Abstract

The domain of this thesis is the Plasma Frequency Probe (PFP), an instrument that determines the density of a plasma by finding the frequency at which a reflected signal has no phase shift. This information would be used to better understand the plasmas in the ionosphere, as they affect communications. A model was created in order to simulate the PFP. It was found that a low quality factor, along with a high resistance value and upper hybrid plasma frequency, were the ideal conditions for finding the plasma density with the PFP. The AD8302 Phase Detector, the device planned for detecting the phase shift created by the plasma, further ensures that a low quality factor would be desirable. However, by adding noise and finding the upper hybrid plasma frequency (through averaging frequencies that result in low enough phase differences and thus voltage from the output of the phase detector), it is found that higher quality factor, lower noise, and a lower compared voltage result in the most accurate estimate of the upper hybrid plasma frequency. Also, the original upper hybrid frequency is a significant parameter, as higher frequencies and frequencies near the edges of the sweep range can compromise accuracy estimates.

Acknowledgments

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Chapter 1 Introduction

1.1 Motivation

The definition of a plasma according to Chen (2006) is "a quasineutral gas of charged and neutral particles which exhibits collective behavior." Quasineutral means that, while there are equal number of positive and negative charged particles (i.e., the plasma overall is neutral), Coulomb forces exist because the charges move independently of one another resulting in local concentrations of a specific charge. Collective behavior means that the motions of a plasma depend on the entire plasma, including remote locations and local conditions (Chen, 2006). Thanks to these properties, plasmas often exhibit unique properties, some of which are not intuitive.

In our universe, 99% exists in the plasma state, the fourth state of matter. Despite our living in the 1% that does not exist in this state, plasmas are found close enough that they can affect many aspects of daily life. For example, the domain of interest for this thesis is the ionosphere, which extends from about 60 km to 1000 km above the Earth. This region of the Earth's atmosphere is ionized mostly by the energy absorbed from ultraviolet sunlight (Carlson, 2004). It has peculiar properties that have varying effects, such as the absorption or reflection of radio waves in certain frequency ranges. Plasma properties can evidence themselves both advantageously and disadvantageously. For example, Earth-to-satellite communication-and control-links are adversely affected by these properties, while other systems use this reflective property to transmit signals over long distances. Thus, changes in the ionosphere have huge implications on modern day communications.

A better understanding of the ionosphere can result in more efficient communications, or warnings as to when a signal is in danger of being lost due to changes in the ionosphere. A property that warrants investigation is the effect of heating by radio waves on plasma properties, and measuring the plasma properties during heating is of interest. One such method of measuring plasma density is with a Plasma Frequency Probe (PFP). The PFP works by sweeping through a range of frequencies with a voltage signal applied to the probe, which excites the plasma. This, in turn, causes the probe's impedance to vary with frequency. The reflected signal is then measured. If the signal frequency passes through the upper hybrid plasma frequency, the phase reflected signal will go through zero. This measurement technique allows us to find the plasma density, an important plasma parameter.

1.2 OSIRIS and Arecibo

OSIRIS (Orbital System for Investigating the Response of the Ionosphere to Stimulation and space weather) is a CubeSat mission design currently underway at The Pennsylvania State University's Student Space Programs Laboratory (SSPL) (Bilén *et al*., 2009). A CubeSat is a miniature satellite with dimensions of ten centimeters per side, and weighing 1.33 kilograms. Because of their small size and mass, they are less expensive and simpler to build and launch. However, small size and mass also limit the satellite payload's functional capabilities. OSIRIS is a trio of satellites that will be launched into orbit in the ionosphere in order to take measurements of the plasma directly. This is preferable to ground-based systems as it can measure local disturbances and fine structure (Swensen, 1989). The three-satellite system enables characterization of the same region at different times, resulting in a better understanding of how changes from heating can correlate to changes in the plasma as a function of time. By partnering with the Arecibo Observatory, which will perform the function of heating the ionosphere, OSIRIS hopes to associate the heating to changes in the ionosphere. In order to accomplish this goal, OSIRIS will use a PFP as part of a Hybrid Plasma Probe (HPP) system (Kummer et al., 2009) to determine the key plasma parameters.

1.3 Thesis Organization

This thesis is organized as follows. Chapter 2 focuses on background information. It begins with plasma fundamentals in order to create a basic understanding of plasma physics. The second topic is the ionosphere. The ionosphere is the region of the atmosphere where plasmas exist, and it is the region of interest for Arecibo and OSIRIS. The third topic is the PFP, which will be used to determine the primary plasma parameter, plasma density. Basics of the PFP, previous work, and a circuit model of an antenna in a plasma are all covered in order to create an understanding of the PFP as well as the parameters that are used to model it.

Chapter 3 is model development. It begins with an overview of the model, followed by an explanation of the four blocks of the model. They are the reference signal model (which creates the reference signal and sweeps through a frequency range), the antenna model (which models the antenna characteristics), the plasma model (which models the plasma characteristics), and the phase detection model (which models the AD8302 phase detector characteristics). The final section is the noise and detection model, which determines the upper hybrid plasma frequency from the phase detector with the addition of noise.

Chapter 4 focuses on simulation results. It determines how both phase and amplitude vary with frequency due to the plasma characteristics. It also determines how antenna characteristics and the AD8302 phase detector affect the model. Finally, it determines plasma parameters from the results, explaining how different parameters affect the accuracy of the PFP.

Chapter 5 summarizes the conclusions and provides future steps that can be taken to further the understanding of the ionosphere and to verify the PFP model.

Chapter 2 Background

2.1 Plasma Fundamentals

As plasmas are quasineutral, they can contain neutral particles but they do not contribute much to the motion of the particles other than in the form of collisions. Ions and electrons can act in very unique ways due to their charges. Coulomb forces and reactions to electric and magnetic fields are a few of the ways in which they can be affected. Ions, however, are very heavy compared to electrons and do not tend to move as easily. Thus, these ions can be thought of as creating a uniform background. When the electrons are displaced due to a perturbation (such as with an electric field), their position will tend to be restored by the Coulomb force. However, due to their inertia, the electrons will overshoot their intended position and then experience a force in the opposite direction, resulting in an oscillation. This electron oscillation is the plasma frequency, which will occur as a natural resonant frequency within plasma that is neither excited thermally nor influenced by a magnetic field (Chen, 2006). The electron plasma frequency is given by

$$\omega_{pe} = \sqrt{\frac{n_e q^2}{\varepsilon_0 m_e}} \ , \tag{1}$$

where

n_e = density of electrons,

q = electron charge magnitude,

ε_0 = permittivity of free space, and

m_e = mass of an electron.

The Earth does, however, have a magnetic field. As an electron that moves results in a current, it feels a force due to the magnetic field. This will be a central force, again resulting in an oscillation as individual electrons tend to move in a circle around the perpendicular magnetic field lines. This oscillation rate is the cyclotron frequency (Chen, 2006). The electron cyclotron frequency is given by

$$\omega_{ce} = \frac{qB_0}{m_e} \ , \tag{2}$$

where B_0 is the magnitude of the magnetic field. These two frequencies are needed to obtain the upper hybrid frequency. Ignoring temperature effects and electric field lines, as they are small enough not to affect the ionosphere (Chen, 2006), the upper hybrid frequency is given by

$$\omega_{\mathrm{uh}}^2 = \omega_{pe}^2 + \omega_{ce}^2 \tag{3}$$

By inserting their definitions and solving for electron density, it is possible to get electron density as a function of the upper hybrid frequency. This is because the other terms either are constants, or can be treated as such, e.g., the Earth's magnetic field. Therefore, the density of electrons or equivalently the plasma density is

$$n_e = \varepsilon_0 \left(\frac{m_e \omega_{\mathrm{uh}}^2}{q^2} - \frac{B_0}{m_e} \right) \tag{4}$$

These equations describe the relationships between plasma frequency, cyclotron frequency, upper hybrid frequency, and electron density. Since plasmas are quasineutral, the electron density is approximately equal to the ion density. The plasma frequency is related to the density of electrons, the charge of electrons, the permittivity constant, and the mass of electrons. The cyclotron frequency is related to the charge and the mass of electrons as well, but it is also related to the magnetic field, which in this case would be the Earth's magnetic field at the altitude of the satellite. The sum of the squares yields the square of the upper hybrid frequency, which is related to the density of electrons. Therefore, we can solve for the density of electrons in terms of the upper hybrid frequency. Electron density is easier to determine than ion density, since not only are ions more difficult to perturb with electrical signals than electrons, but positive ions also vary with the elements that are ionized, resulting in different masses. Because the upper hybrid frequency can be determined with the PFP, it is a matter of simple math to determine the plasma density. The electron plasma density is one of the plasma's most important characteristics, as free electrons are what cause most of the effects on communications (Swensen, 1989).

2.2 Ionosphere

The mesosphere and the ionosphere, the upper two regions of the Earth's atmosphere, both consist of relatively cool and low density plasma. One of the differences between the two relates to whether temperature rises or falls with respect to altitude, as shown in Figure 1. Both are ionized mostly by ultraviolet light from the sun, but other factors such as high speed solar wind and ionization of meteorites produce some of the ions or the ionization of gases in the upper atmosphere (Siegel, 2004).

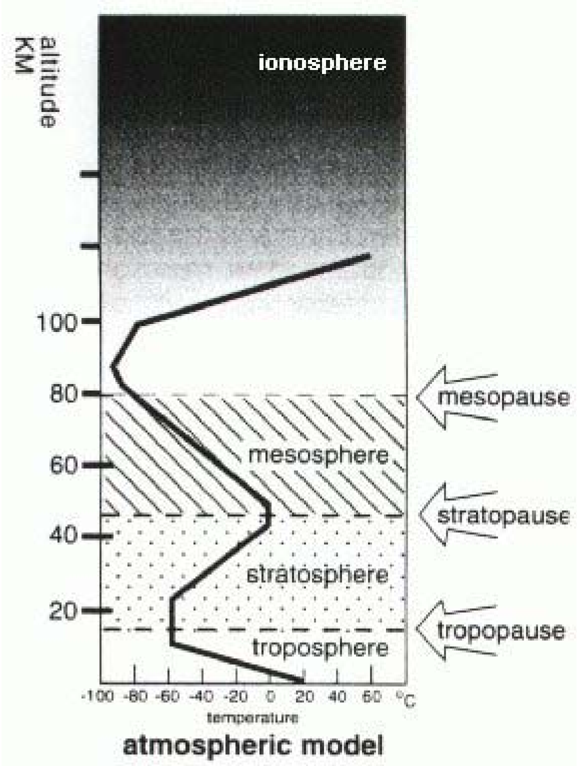

Figure 1 A model of the Earth's atmosphere showing the various parts of the atmosphere and how temperature varies with altitude (Atmospheric Sci. Res., 2002).

As stated previously, the existence of these layers is responsible for the absorption and reflection of radio waves. They consist of three different layers, labeled the D, E, and F regions. These properties of these regions vary with altitude due to the molecules that are ionized and the forms of radiation that they absorb. In all of these layers, the plasma approximations of quasineutrality and collective behavior both remain valid. Thus, when combined with the Earth's magnetic field, the mesosphere and the ionosphere form a structure that can be measured by instruments such as the PFP. This structure varies with everything from the solar cycle (note that sunspots, coronal mass ejections, and solar wind all vary with the solar cycle), to simple changes from day to night (Siegel, 2004). Thus, a man-made disturbance such as the heating from Arecibo can also alter these regions and could be studied through the measurements of the PFP.

2.3 Plasma Frequency Probe (PFP)

2.3.1 Basics of the PFP

The impedance of the antenna is affected by the medium in which it is immersed. The plasma can be treated as a dielectric with a relative permittivity, which is related to a variety of its properties, including density, temperature, collision frequency, and magnetic field. These properties change depending on the signal emitted by the antenna that excites the plasma. Thus, the plasma acts as a reactive load, which can change from inductive to capacitive. This crossover occurs at the upper hybrid frequency because of the admittance of the antenna is related to the inverse of the of the impedance effect. Thus, when the signal is in resonance with the plasma, it changes from inductive to capacitive, resulting in zero phase shift (Siegel, 2004).

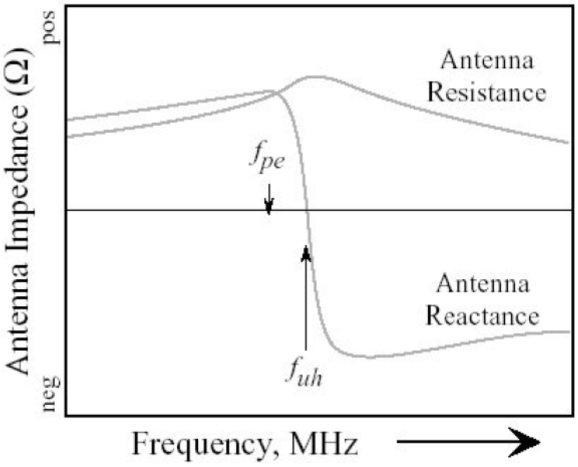

Figure 2 A graph of antenna impedance vs. frequency, showing how the reactance (and phase shift) cross zero at the upper hybrid frequency (Siegel, 2004).

Following these basic ideas, if an instrument were to sweep a range of frequencies and find the frequency at which the load changed from capacitive to inductive, the upper hybrid frequency could be found, and subsequently, the electron plasma density. This results in the PFP being insensitive to spacecraft potential changes, probe surface contamination, and even its alignment relative to the magnetic field. These are all advantages over other types of plasma probes. Also, if implemented correctly, they can have very effective time and frequency resolution, resulting in the ability to resolve small-scale plasma instabilities (Carlson, 2004).

2.3.2 Previous Work

The plasma frequency probe concept has been around since the late 1960s (Carlson, 2004). In 1989, Swensen explored ways to characterize, evaluate, and improve the Utah State University PFP design. Carlson (2004) and Siegel (2004) both worked on instruments that combined a series of plasma instruments into superior probes. Derivative work from Siegel (2004) and others, specifically, is scheduled to be integrated onto OSIRIS (Kummer *et al*., 2009). The Hybrid Plasma Probe (HPP) instrument will include the PFP, a swept- and fixed-bias Langmuir probe, and a fast temperature probe. Since the probes share some of the same components, the mass, volume, and power consumed all are less than if separate instruments were used. This is a very desirable outcome on a small satellite, which itself needs to be low cost, low mass, and low volume. Although this HPP system could only run in only one instrument mode at a time, it combines the advantages of each of these probes. Carlson's work was used in this work primarily as a reference as it contained good information about the PFP, and he had also modeled components using MATLAB Simulink.

2.3.3 Circuit Model of Antenna in a Plasma

A circuit model of an antenna in a plasma consists of two parts. The first, the sheath resonance, consists of a series *RLC* (resistor–inductor–capacitor) circuit and the second, upper hybrid resonance, consists of a parallel *RLC* circuit. Since the upper hybrid frequency is of interest, the series part of the circuit can be ignored (Carlson, 2004). This results in the parallel *RLC* circuit shown in Figure 3, with the transfer function

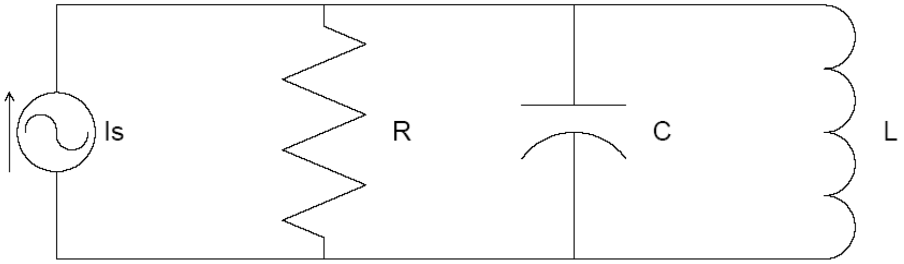

Figure 3 A parallel *RLC* circuit. A plasma can be modeled using this with *R*, *L*, and *C* relating to different plasma parameters.

$$Z(s)=\frac{V_0}{I_s}=\frac{\frac{1}{C}s}{s^2+\frac{1}{RC}s+\frac{1}{LC}}\ , \qquad (5)$$

where

$C =$ model circuit capacitance,

$R =$ model circuit resistance,

$L =$ model circuit inductance,

$I_s =$ model circuit ideal current source, and

$V_0 =$ model circuit voltage.

The plasma-immersed antenna can be modeled as a simple parallel *RLC* circuit with an ideal current source in parallel. Its capacitance and inductance values are based upon the resistance-based scaling value, the upper hybrid frequency, and a quality factor. The upper hybrid frequency is simply the resonant frequency, and thus related directly to *C* and *L*, i.e., (Carlson, 2004)

$$\omega_{\mathrm{uh}}=\frac{1}{\sqrt{LC}}\ . \qquad (6)$$

The quality factor, *Q*, is related to *R*, *L*, and *C*. It is the ratio of the resonant frequency to the system bandwidth and is also defined as the ratio of the maximum energy stored compared to the energy dissipated per cycle. The system loses energy due to the collisions in the plasma, so as more collisions occur, more energy is lost, and *Q* is lowered (Carlson, 2004). The relationship of *Q* to *R*, *L*, and *C* is

$$Q = R\sqrt{\frac{C}{L}}\ . \tag{7}$$

Here, *R* is simply a scaling factor for the response magnitude. When these values are placed in the transfer function of the parallel *RLC* circuit, the resulting equation is

$$Z(s) = \frac{R\frac{\omega_{\text{uh}}}{Q}s}{s^2 + \frac{\omega_{\text{uh}}}{Q}s + \omega_{\text{uh}}^2}\ . \tag{8}$$

From this transfer function, the following magnitude and phase changes can be determined

$$|Z(j\omega)| = \frac{R}{\sqrt{1 + Q^2\left(\frac{\omega}{\omega_{\text{uh}}} - \frac{\omega_{\text{uh}}}{\omega}\right)^2}}\ \text{, and} \tag{9}$$

$$\theta(j\omega) = -\tan^{-1} Q\left(\frac{\omega}{\omega_{\text{uh}}} - \frac{\omega_{\text{uh}}}{\omega}\right)\ . \tag{10}$$

The *R* value is not important to determining the upper hybrid frequency. This can be seen in Eqn. (10) for the phase, which goes to zero when the frequency is equal to the upper hybrid frequency. Thus, if we can detect when the phase is zero and relate that to a frequency, we can find the upper hybrid frequency, which leads to plasma density as was shown earlier. However, the quality factor does in fact have an effect on this curve. The larger the *Q*, the more quickly the phase goes to zero, thus making it harder to the zero crossing point. This results in an interesting fact that more collisions in the frequency actually result in a more detectable plasma density. This characteristic will be covered in greater detail in Chapter 4.

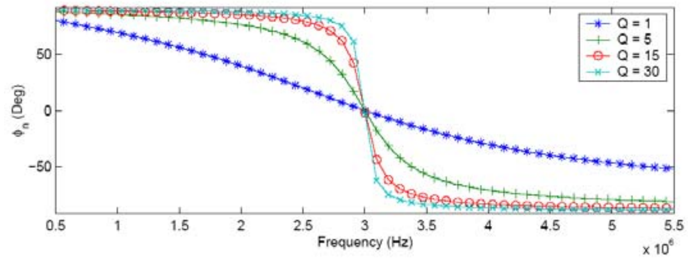

Figure 4 A graph relating phase to frequency. A lower *Q* (quality factor) results in a slower change around the upper hybrid frequency (Carlson, 2004).

Chapter 3 Model Development

3.1 Model Overview

In order to better understand the PFP, a model was developed using MATLAB Simulink. The model is to be used to compare with test results in order to determine if the outcome was expected, as well as to find any other issues the probe might have during development or operation. The PFP model was broken into four separate parts. Part one was the reference signal, which is the swept-frequency signal (in this case a sine wave). Part two is the antenna, which adds its own distortion effects to the signal when inserted in the plasma by inducing gain and phase changes. Part three is the plasma. By using the plasma parameters of quality factor, upper hybrid frequency, and resistance value as modeled by an *RLC* circuit, the plasma's phase and gain changes can be accounted for. Finally, the phase detection block determines the difference between the plasma-altered signal and the antenna-altered signal and converts it using the AD8302 Phase Detector specifications in order to get values within the proper voltage ranges. Figure 5 displays this block diagram of the model and the manner in which that these four blocks are connected. The other parts of this overall view are simply intended to display the results of the process. The *x–y* graphs (gain vs. freq. and phase vs. freq.) allow the model to compare gain and phase directly to frequency, while the scopes compare them to time. The display shows what the current value is, in real time, at a given point.

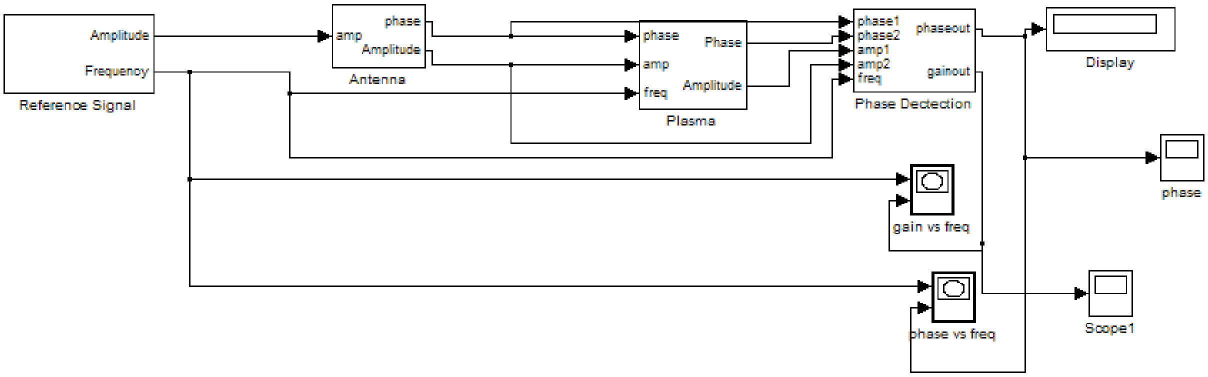

Figure 5 The block diagram of the model. The reference signal generates the signals with different frequencies, while the antenna and plasma alter both its phase and its gain. The phase detector finds these changes.

3.2 Reference Signal Model

The first element of the PFP is the reference signal. One challenge with the reference signal is assuring that it sweeps through a target range of values that includes the upper hybrid plasma frequency. The lower bound of frequencies was chosen to be 500 kHz, and the upper bound 26 MHz. To set up the frequency sweep, a free-running counter was used to step through different frequencies. A 256-step process was chosen; by multiplying this counter by 100,000 and adding it to the base value 500 kHz, we were able to linearly step from 500 kHz to 26.1 MHz. Using a sine wave block with an external time reference, we were able to multiply this changing frequency value by a digital clock value and input it to the sine wave block (labeled “Reference”). This served the dual purposes of providing a time stamp and sweeping through the frequency range. The outputs of the block include the sine wave (labeled “Amplitude”) and the current frequency (labeled “Frequency”). A scope was added to view the unmodified reference signal.

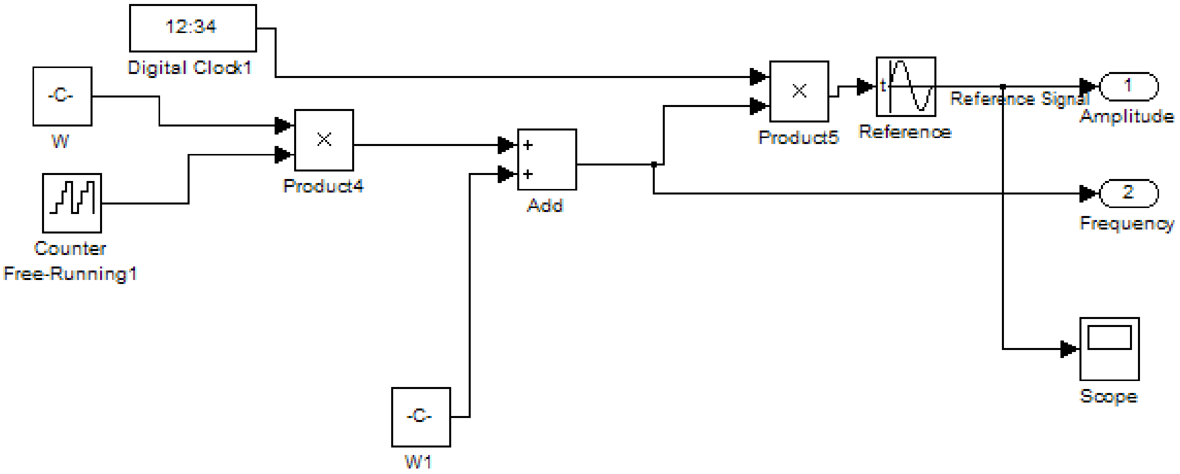

Figure 6 The reference signal model. W is the step frequency (which is changed by the free running counter) and W1 is the starting frequency. By combining these with a digital clock, they create a sine wave signal that sweeps through a chosen set of frequencies.

3.3 Antenna Model

The antenna is the first part of the PFP that affects the reference signal. Its input is the reference signal (labeled “amp”), which is multiplied by the gain of the antenna and becomes the output Amplitude. The phase shift of the antenna, the first phase shift encountered, uses the original signal’s phase as zero. The phase shift of the antenna becomes the output phase.

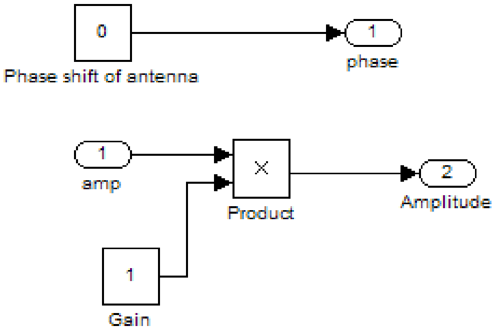

Figure 7 The antenna model. The antenna has an inherent affect on the reference signal, as indicated by the phase and gain.

3.4 Plasma Model

The plasma model uses the circuit model of the plasma described in Chapter 2. By using the basic plasma parameters Q, R, and ω_{uh}, along with the current frequency of the reference signal, we can model the plasma's effects on the signal's amplitude and phase. The inputs are (1) phase (which is the phase shift caused by the antenna), (2) amplifier (the reference signal modified by the gain of the antenna), and (3) frequency (the current frequency of the reference signal), as seen in Figure 8. The plasma model outputs the new phase and modified signal at Phase and Amplitude respectively. The equations used to modify the amplitude and phase are in Section 2.3.3, using Eqn. (9) for gain and Eqn. (10) for phase. By using a series of math blocks, such as add, subtract, and product, these equations were implemented as shown in Figure 8.

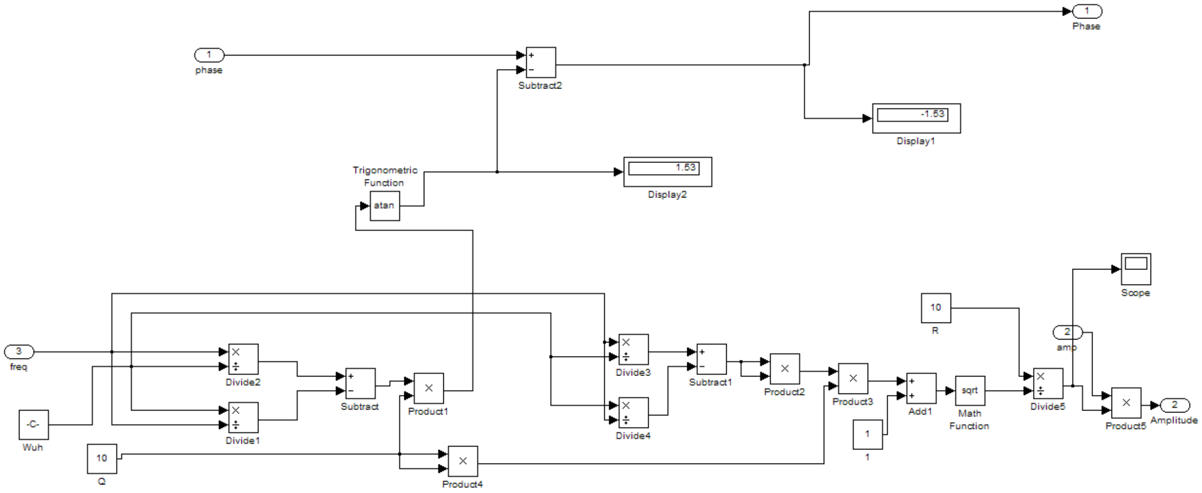

Figure 8 The plasma model. The plasma alters both the gain and phase of the signal, which was already altered by the antenna, based on three plasma parameters and the current frequency of the signal. This model outputs the new phase and amplitude.

3.5 Phase Detection Model

The phase detection model performs three primary functions. First, it determines the phase difference between the plasma and the antenna model outputs. Second, it finds the gain of the plasma by dividing the plasma model gain output by the antenna model gain output. Finally, these two values are converted to voltage values by the AD8302 Phase Detector, thus enabling a direct comparison between test results and simulation results.

The inputs of this model are the antenna model phase output (“phase1”), the plasma model phase output (“phase2”), the signal after modification by the plasma model (“amp1”), the signal after modification by the antenna model (“amp2”), and the current frequency of the reference signal (“freq”). The frequency is used to create the plots of gain and phase against frequency before they are modified by the chip. Through use of the datasheet, we determined the range of voltage values and their corresponding phase and gain values. By dividing the maximum voltage (1.8 V) by the maximum phase (90° or π/2) and gain (30 dB) values, a constant was determined that scaled the model values to what the chip outputs. However, other effects from the chip were considered. For instance, the chip does not recognize negative phase values. Therefore, the phase difference must be put through an absolute value block. The gain is measured in decibels by the chip, and it has a range of −30 dB to 30 dB. Thus, the gain must first be converted to decibels, and then put through a series of if statements that cap the voltage at ±30 dB. The effects of the AD8302 phase detector are discussed in greater detail in Chapter 5.

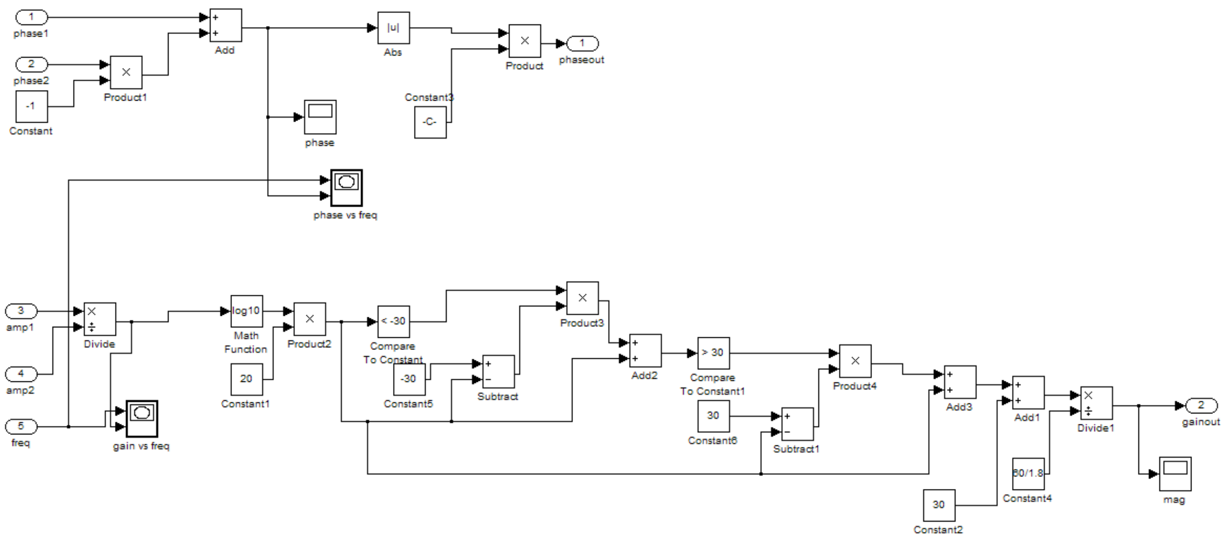

Figure 9 The phase detection model. The phase detection model first finds the difference in the phase between the plasma model and the antenna model, along with finding the plasma gain by dividing the plasma signal by the antenna signal. It then converts these values to the voltage values that would be output by the AD8302 phase detector chip.

3.6 Noise and Detection Model

The noise detection block was added in order to perform two functions. The first is to add noise to the signal generated by the AD8302 phase detector. This was done by adding a uniform random number generator to the phase difference output from the phase detection block. In order to avoid negative voltages an absolute value block was added. The second purpose of the block is to find the upper hybrid plasma frequency. There are two steps to finding this frequency. First, one must determine the minimum starting voltage required to initiate the sweep range that will contain the target frequency. This is done using the compare-to-constant block. Second, the frequencies below this value are averaged together. Since the signal should be approximately symmetric around the upper hybrid frequency, this should give a good estimate for it while also averaging out any outliers due to noise causing the signal to jump out of the “interesting” voltage range. This was done by using memory blocks to store the frequency values, adding them together, and keeping a running counter of the number of frequencies acquired (using an addition block and a memory block). The added frequencies are then divided by the counter, resulting in the averaged upper hybrid frequency.

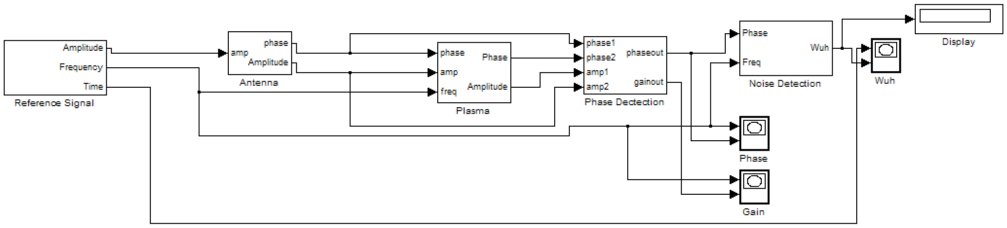

Figure 10 A block diagram with noise.

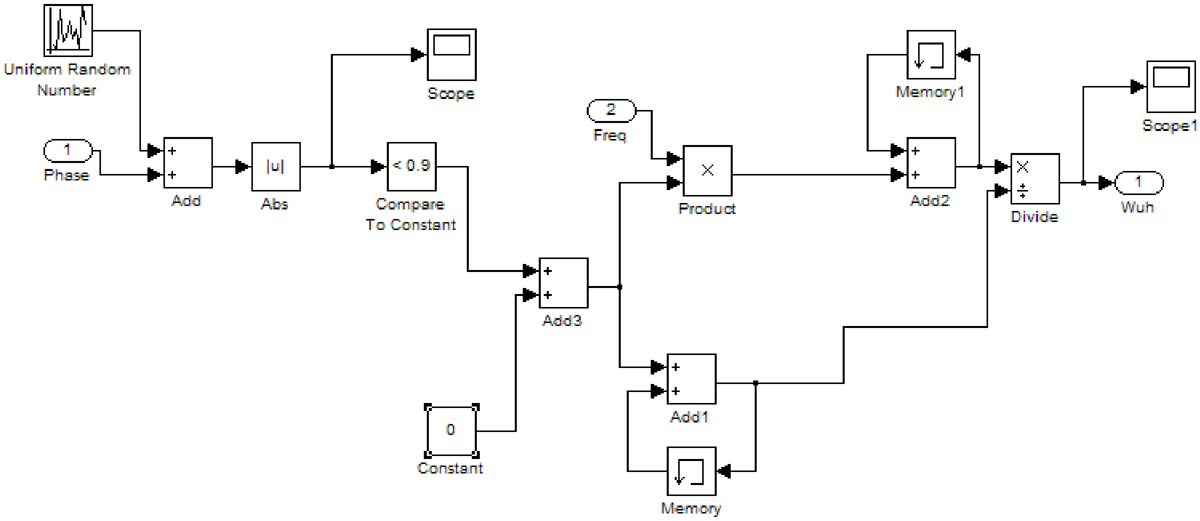

Figure 11 The noise detection model. The block first adds noise to the phase difference signal. It then finds the upper hybrid plasma frequency by averaging the frequency values together when the phase difference is below a certain value.

Chapter 4 Simulation Results

4.1 Phase vs. Frequency

The phase shift of the plasma is determined by Eqn. (10), which shows that the phase is related to the frequency of the reference signal, the upper hybrid frequency of the plasma, and the quality factor of the plasma. Since the upper hybrid frequency and quality factor are constants in any given simulation, the phase changes only with the reference signal's frequency. By varying the quality factor and upper hybrid frequency, we can observe their effects on the phase over a certain range of reference frequencies.

First, the plasma's upper hybrid frequency will be varied. Figure 12 and Table 1 show the main principle upon which the PFP works. By changing the upper hybrid plasma frequency, the zero crossing of the phase shift vs. frequency shifts. It crosses zero at the upper hybrid plasma frequency. Thus, as the upper hybrid plasma frequency is increased, the graph is shifted to the right. It is worth noting that the higher frequencies do not cross the zero as tightly as the lower frequencies do.

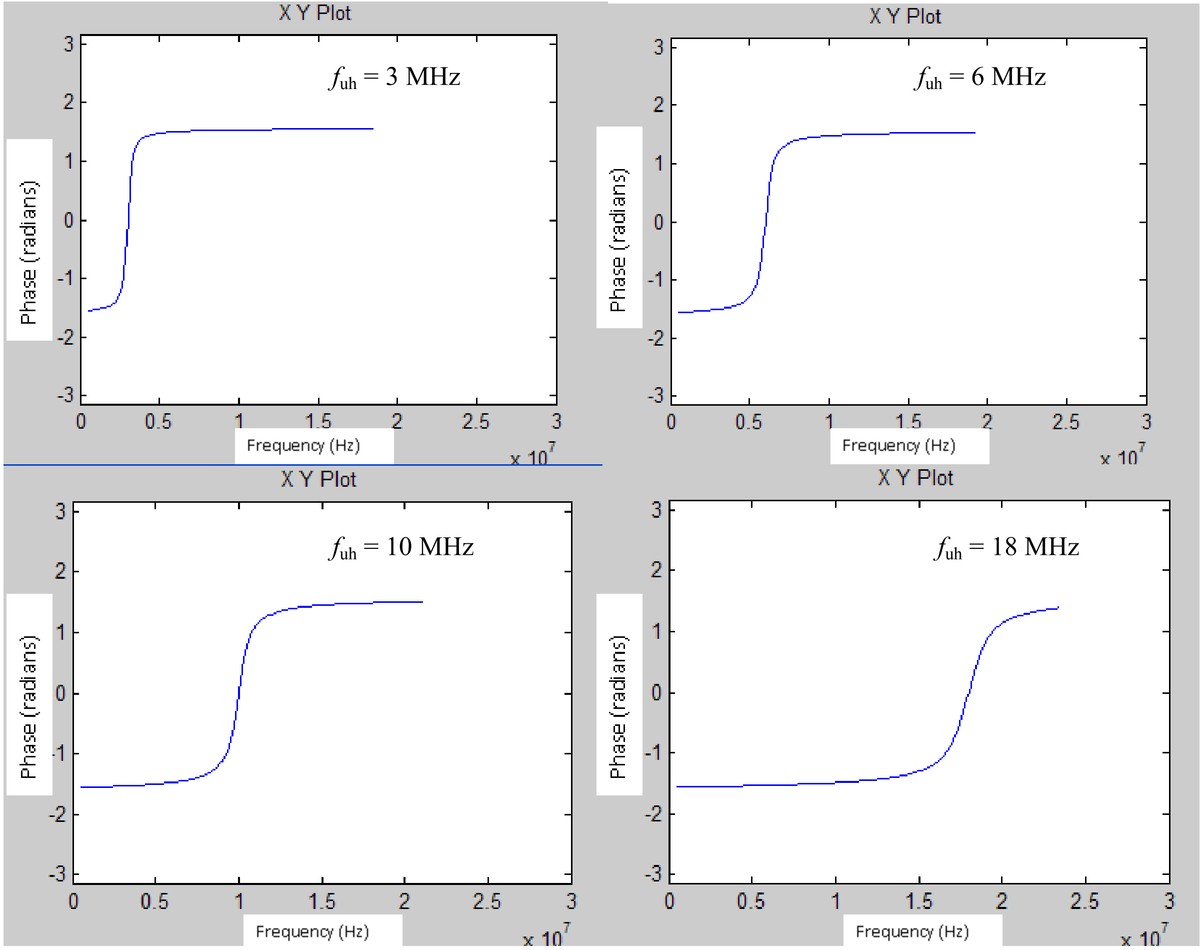

Figure 12 Phase vs. frequency plots with varying upper hybrid plasma frequency. Quality factor remains constant at 10.

Table 1 Relates plasma parameters to the frequency at which the phase difference is zero.

Zero Crossing Frequency Compared to Plasma Parameters			
Q	***R***	***f_{uh}* (MHz)**	**Zero Crossing Frequency (MHz)**
1	1	10	10
5	1	10	10
10	1	10	10
15	1	10	10
10	0.8	10	10
10	1	10	10
10	5	10	10
10	10	10	10
10	1	3	3
10	1	6	6
10	1	10	10
10	1	18	18

Next, the quality factor's effects are studied. As the quality factor increases, it results in a sharper change from negative to positive phase at the upper hybrid plasma frequency. This results in more and more time being spent at the maximum and minimum values. This can have interesting results when applied to the AD8302 phase detector, which will be discussed more in Section 4.4.

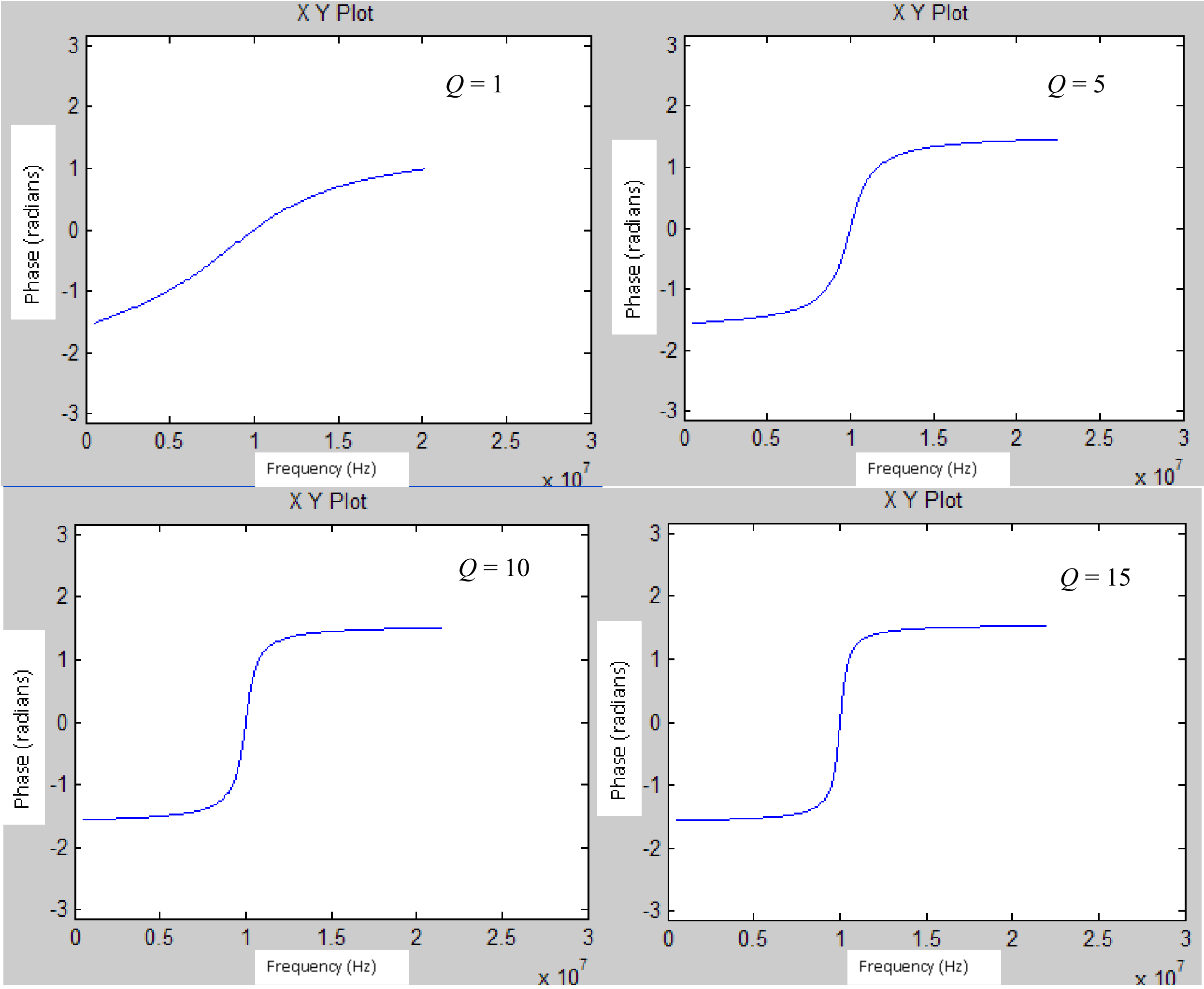

Figure 13 Phase vs. frequency plots with varying quality factor. Upper hybrid plasma frequency remains constant at 10 MHz.

4.2 Amplitude vs. Frequency

The gain of the plasma is determined by Eqn. (9). It is related to the resistance value of the circuit model, the quality factor, and the upper hybrid frequency of the plasma. Again, it varies with the sweeping reference signal frequencies. While the gain is not of primary interest to the PFP, gain has a direct affect on the AD8302 performance in detecting a signal and determining phase. With this in mind, the different plasma factors are again varied, in order to determine if plasma gain is problematic. In Figure 14, increased resistance shows an increase in the maximum gain. The gain is zero for most of the frequency range, except for the region near the upper hybrid frequency. Therefore, a reflected signal might not be detected unless it were close to the upper hybrid plasma frequency. Also, the higher the resistance, the larger the gain would be around this frequency.

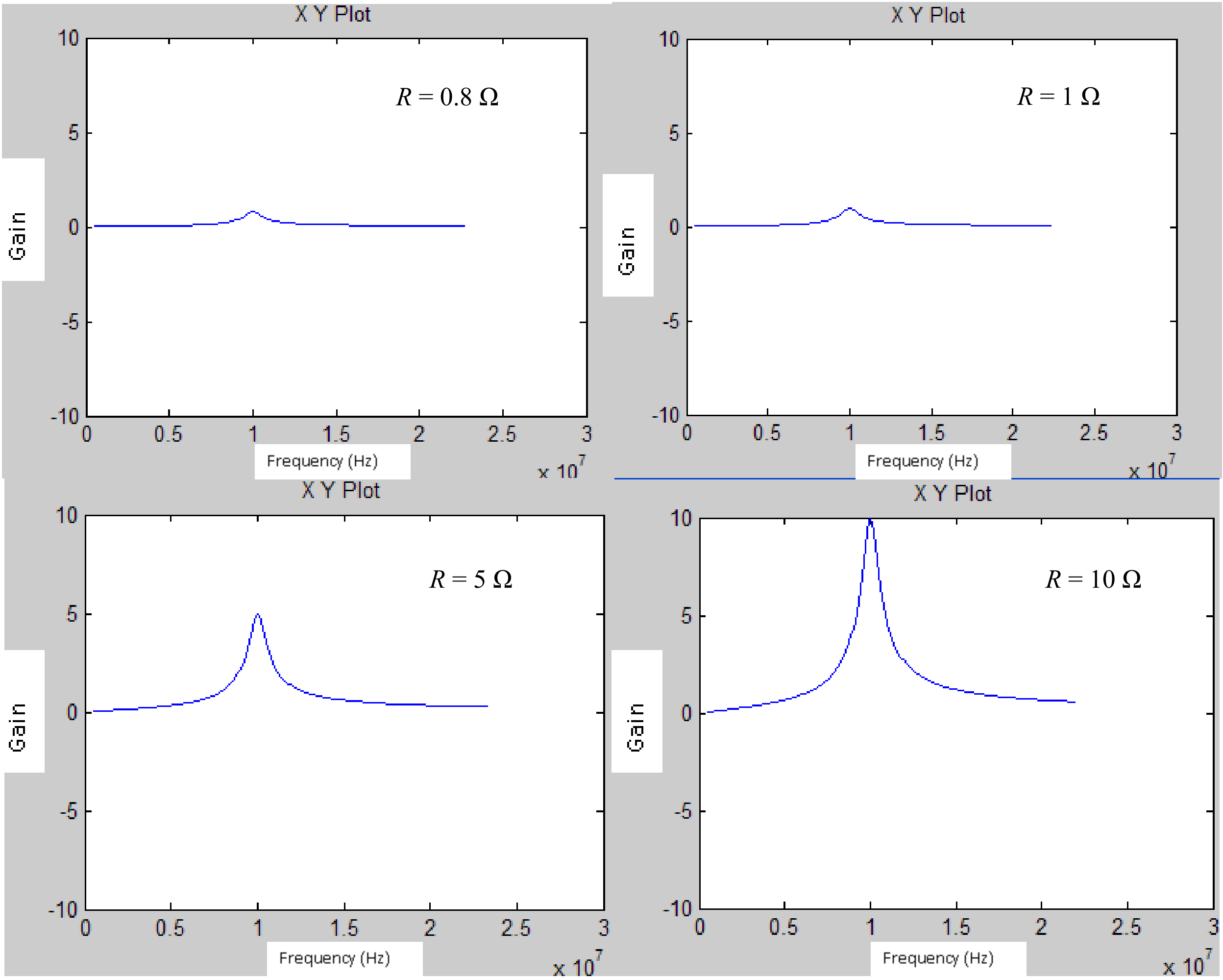

Figure 14 Gain vs. frequency plots with varying resistance. Upper hybrid plasma frequency remains constant at 10 MHz and quality factor remains constant at 10.

In order to verify that the upper hybrid frequency is what causes the spike to be there, it will be the next parameter that is varied. In Figure 15, the upper hybrid plasma frequency shifts the response to the right as it increases much in the same fashion that it changed the phase. The upper hybrid frequency has a secondary effect on the gain, however, in that, not only does it determine where the maximum gain is, but the higher the upper hybrid frequency the larger the range of frequencies that are not zeroed out. This means that it is possibly easier to determine higher upper hybrid frequencies, as a larger range of frequencies can be detected resulting in a more complete phase vs. frequency graph.

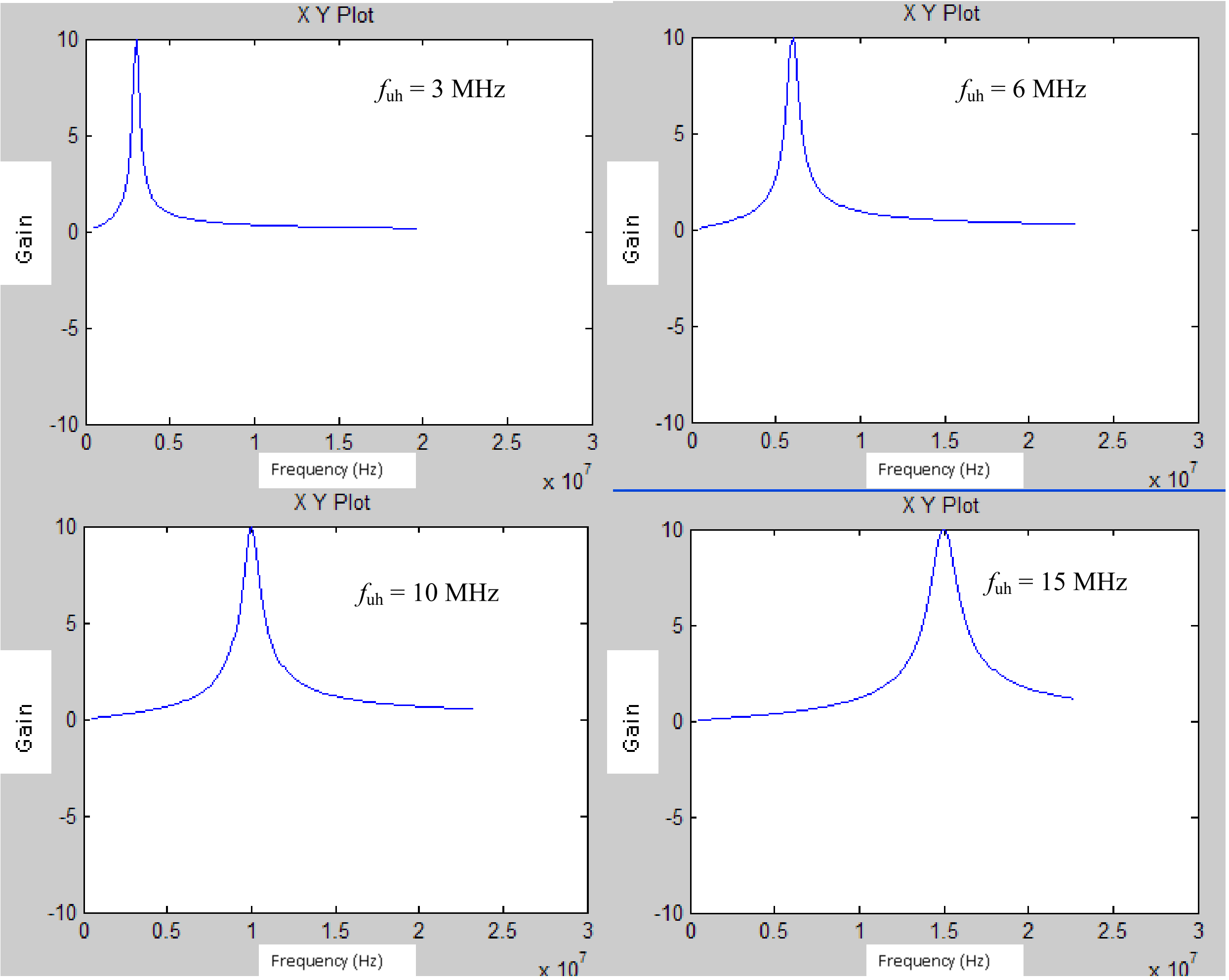

Figure 15 Gain vs. frequency plots with varying upper hybrid frequency. Resistance remains constant at 10 Ω and quality factor remains constant at 10.

Finally, the effects of quality factor are studied. Figure 16 shows that the lower the quality factor, the larger the gain for frequencies farther from the upper hybrid plasma frequency. This means that a lower quality factor will actually result in a more complete graph of phase vs. frequency, since more frequencies will be able to be detected and identified. The results demonstrate that a high resistance, with a low quality factor and a high upper hybrid frequency, results in the best conditions for phase detection.

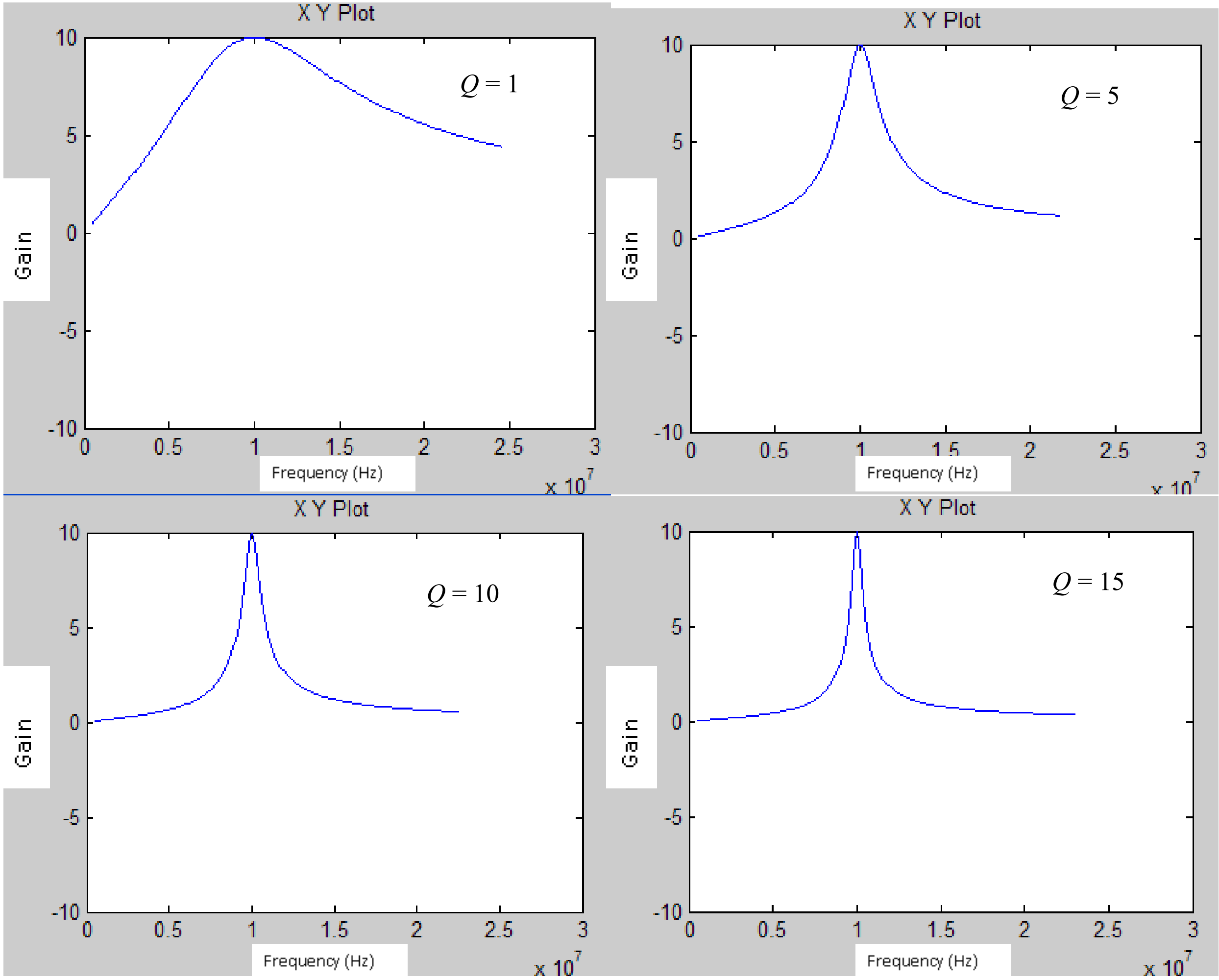

Figure 16 Gain vs. frequency plots with varying quality factor. Resistance remains constant at 10 Ω and upper hybrid frequency remains constant at 10 MHz.

4.3 Antenna Effects

So far, the antenna characteristics of unity gain and zero phase shift have been held constant. Next, the gain and phase will be shifted independently in order to determine if they can cause problems. The two assumptions are that antenna gain and phase shift do not vary with reference signal frequency and that the AD8302 phase detector chip will be able to compare the signal after it is changed by the antenna to the plasma changes.

First, the gain will be varied. Figure 17 shows that the antenna gain has no effect on the gain on the plasma. This means that as long as the overall gain is neither too low to detect nor so high that it can burn out components, then it will not adversely affect finding the phase shift of the plasma.

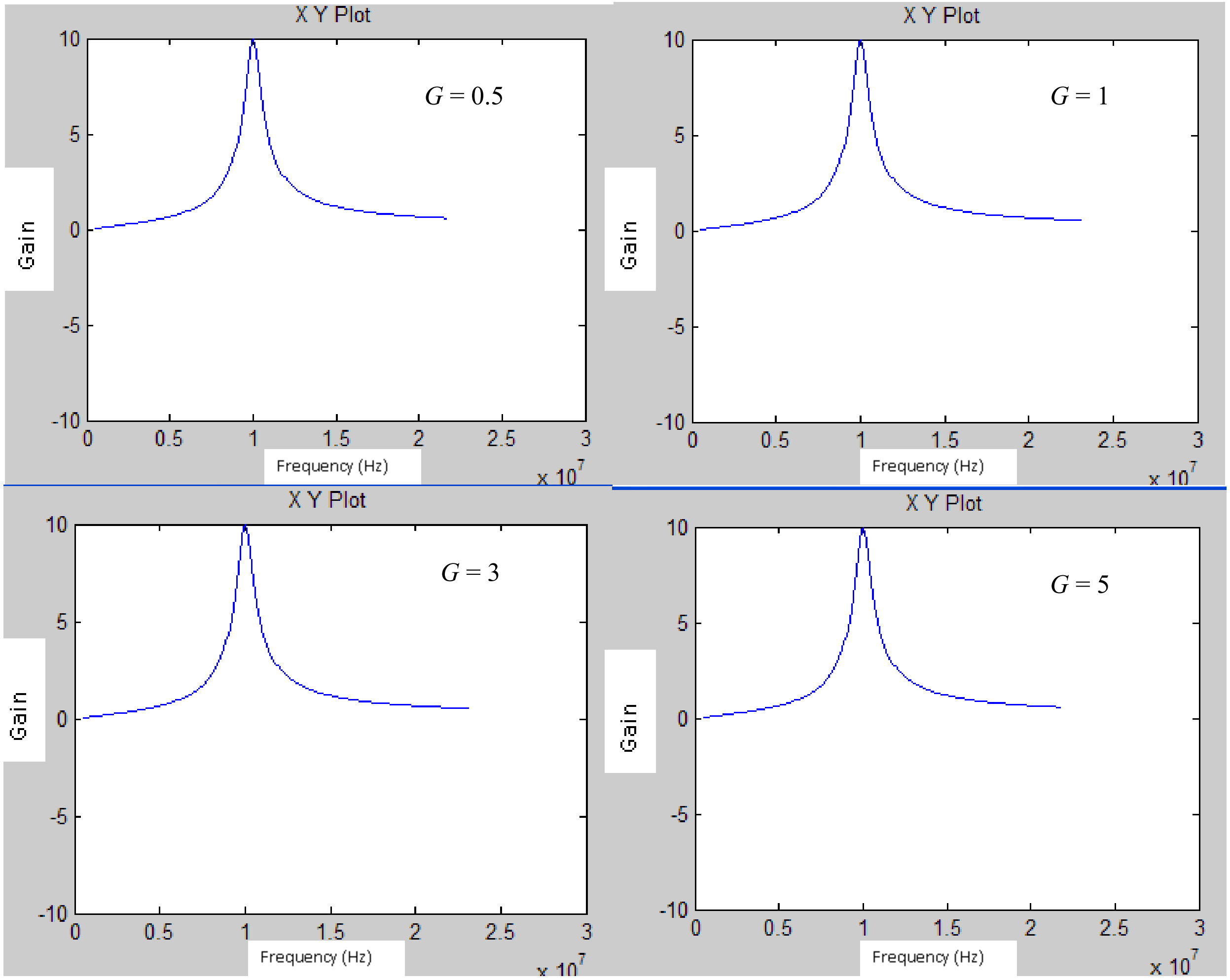

Figure 17 Gain vs. frequency plots with varying antenna gain. *G* is antenna gain.

Next, the phase of the antenna will be observed. Again, Figure 18 shows the antenna has no effect on the signal output. This means that overall the antenna's inherent parameters should not interfere with determining the phase for the PFP.

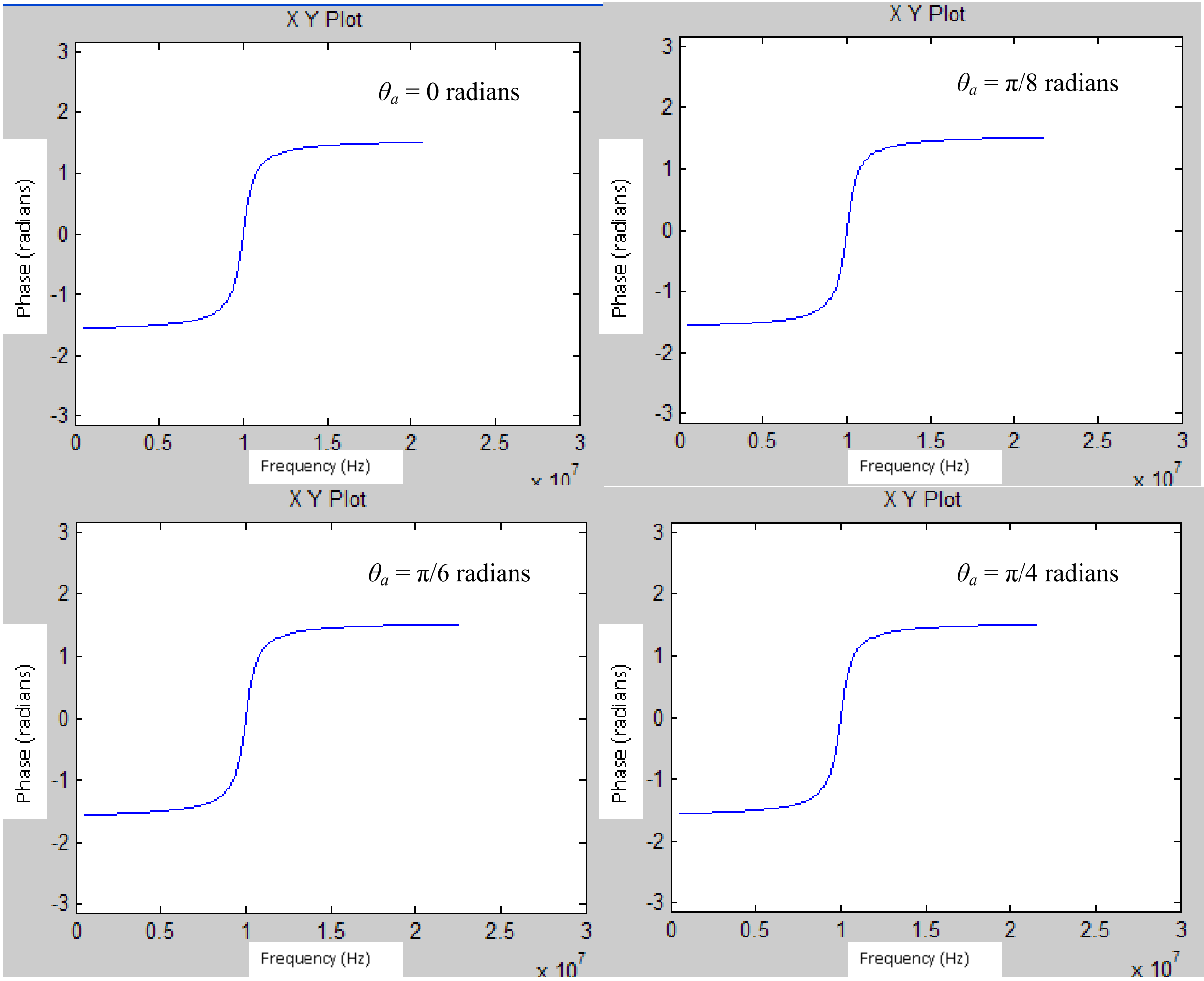

Figure 18 Phase vs. frequency plots with varying antenna phase. θ_a is antenna phase.

4.4 AD8302 Phase Detector Effects

The AD8302 phase detector adds several complications to the PFP, those most easily seen being the scaling of phase and gain values to the rail voltages. Other effects, however, could be more damaging. For instance, it has a maximum and minimum gain that it can detect and it also does not differentiate between positive and negative phase.

We will begin by studying the gain. The most notable change in Figure 19 is that the phase detector determines the gain in decibels. However, this along with the scaling would have little effect on its abilities to fulfill its role within the PFP. However, if the gain is too large or small, clipping can occur (Figure 20). This means that the resistance value must be within a certain range in order for the phase detector to accurately measure the gain. Whether or not this would affect the phase detector's ability to determine when the phase reaches zero is not certain.

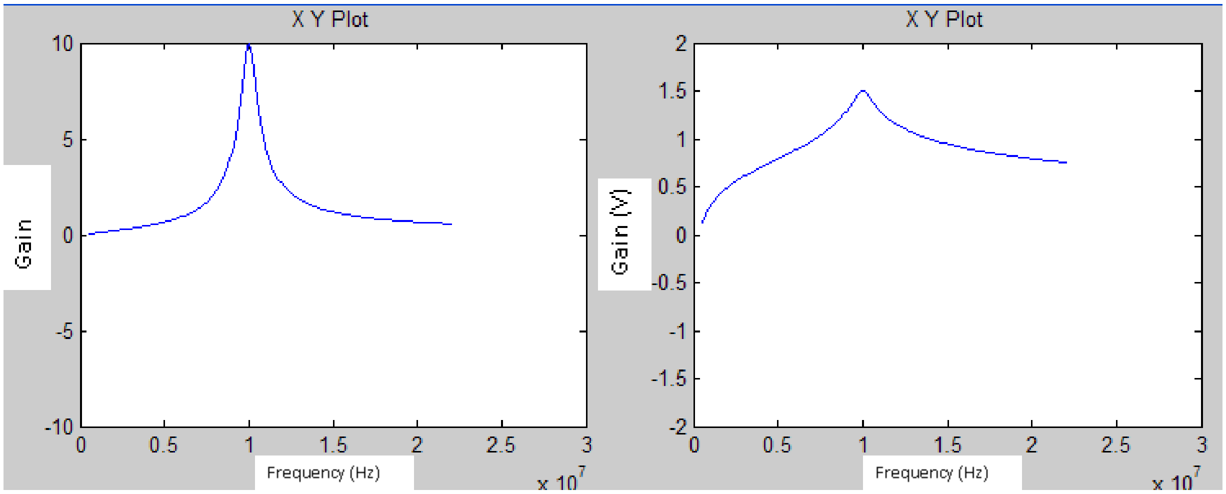

Figure 19 Gain vs. frequency plots. On the left is before going through the phase detector, and on the right is after going through the phase detector.

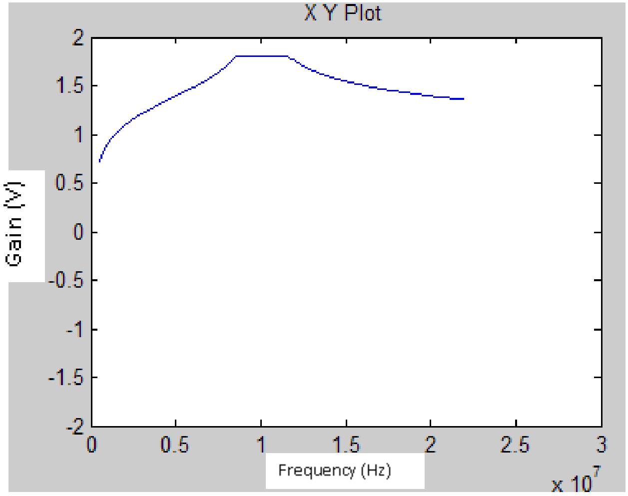

Figure 20 Gain vs. frequency plot showing clipping occurring due to high resistance.

Next, we examine the phase response of the detector. Since the phase detector does not distinguish between positive and negative phase, it has an absolute value effect on the phase vs. frequency. Problems occur when the quality factor is too high, since only a limited number of frequencies can be used over a wide range. If the quality factor is too high, it results in a very narrow notch that could go undetected, resulting in what would look like a flat line (Figure 22). Therefore, it appears that a lower quality factor (more collisional plasmas) provides the best results with the AD8302 phase detector.

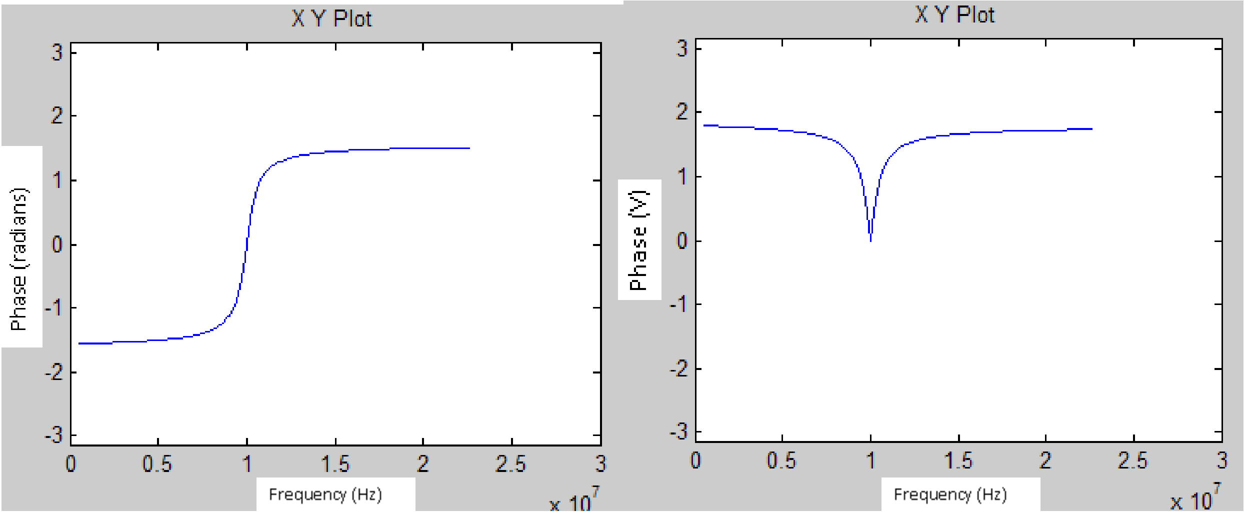

Figure 21 Phase vs. frequency plots. On the left is before going through the phase detector, and on the right is after going through the phase detector.

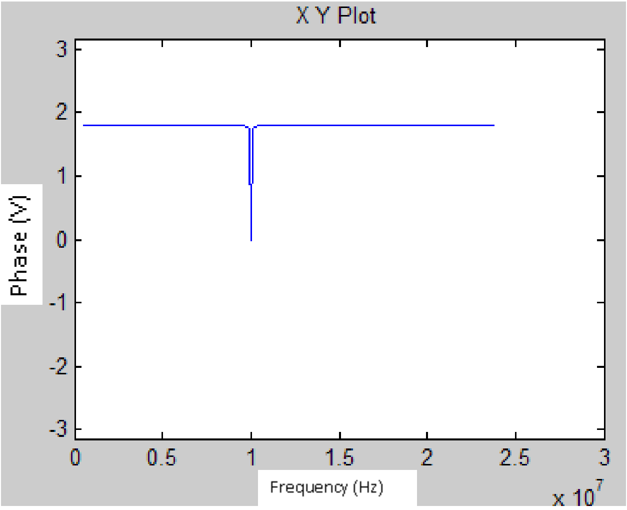

Figure 22 Phase vs. frequency plot with a high quality factor.

4.5 Determining Plasma Parameters from Results

First, we shall go over the noise detection block's effects on the signal. The noise detection block simply adds some Gaussian noise to the phase detection of the model. The noise based on a percentage of the signal's maximum strength (voltage), which is 1.8 V. As an example, 25% would be a possible addition of 0.45 V, or ±0.225 V (Figure 23). However, due to the absolute value in the noise detector, at the parts of the graph near zero the most noise will be 0.225 V. This is due to the fact that after going through zero it will simply become positive again. Therefore, higher error percentages will be needed to impact the averaged frequency significantly.

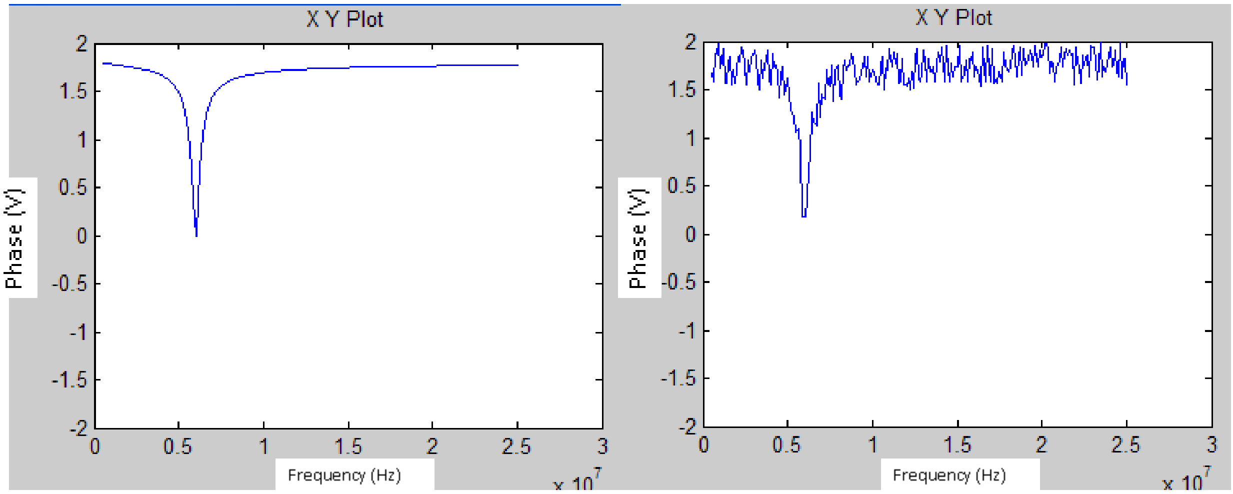

Figure 23 Phase vs. Frequency and Phase with Noise vs. Frequency. Noise is within 25% of the original signal's maximum voltage.

There are a few parameters to consider when determining the noise's effect on finding the upper hybrid plasma frequency. The first is the upper hybrid plasma frequency itself. Since there is a set range that is being swept, it is of interest to find if the entire range results in equal levels or error. In other words, do higher or lower frequencies relative to the swept frequency range result in different amounts of error. In Figure 24, it shows that the frequency is surprisingly unaffected by being at the extremes of the swept frequency range. While it does seem to be affected more at higher frequencies, it still is not to a point where it causes an unreasonable amount of error (about 0.4 MHz lower than the 25 MHz signal). The reason for the difference is that, at lower frequencies, the notch around the upper hybrid plasma frequency becomes smaller, as discussed in the phase vs. frequency section. The result is more frequencies giving smaller phase shifts (and thus lower voltages from the phase detector), allowing more frequencies to be averaged together. Thus, the higher end of the swept frequencies results in more frequencies below the upper hybrid plasma frequency being averaged together, creating an average that is skewed low. The effect is especially noticeable when combined with low quality factor, as in Figure 25.

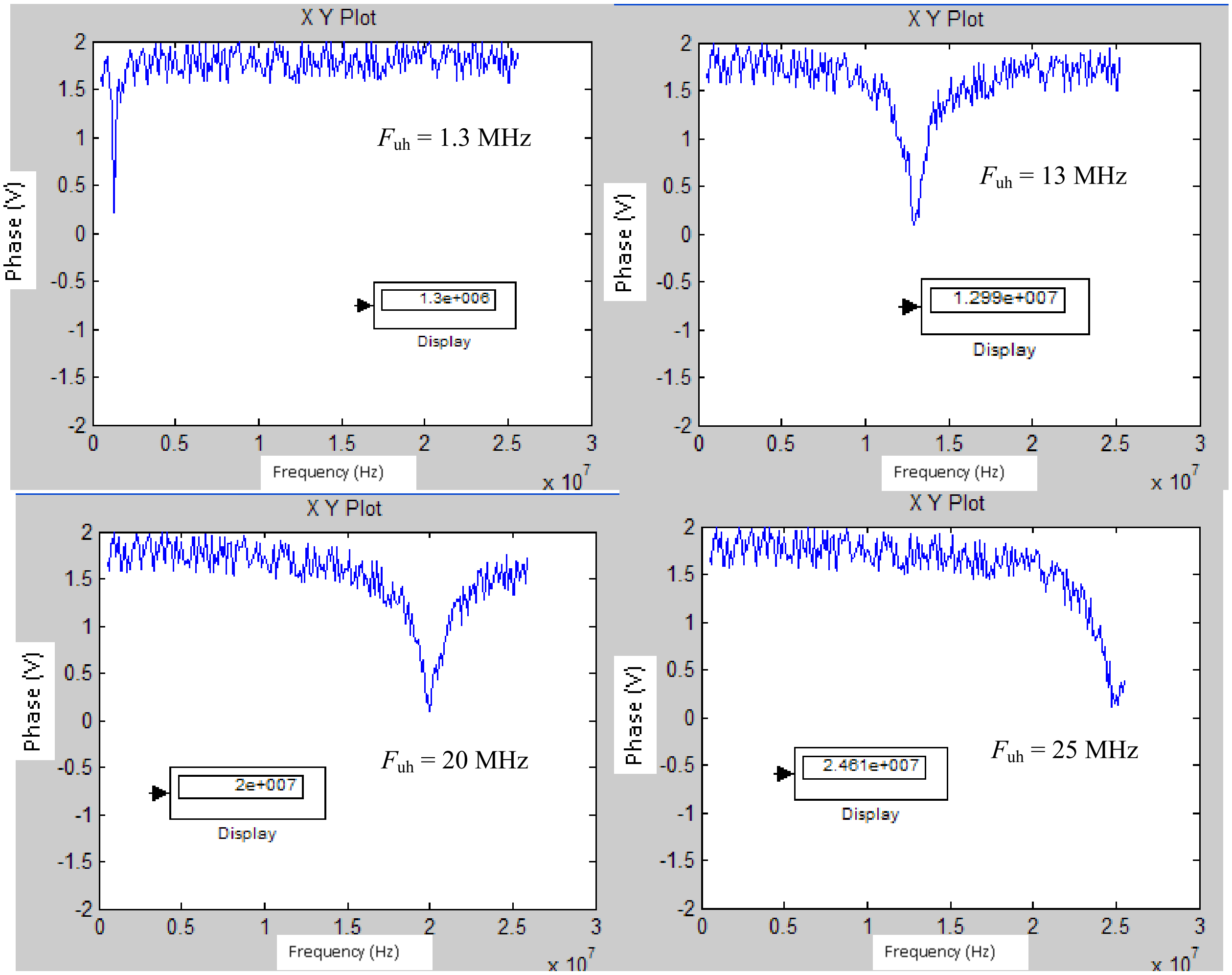

Figure 24 Phase vs. Frequency with noise, with display of averaged upper hybrid frequency. *Q* is held constant at 10, noise is held constant at 25%, and compared voltage is held constant at 0.9 volts. The upper hybrid frequency is varied.

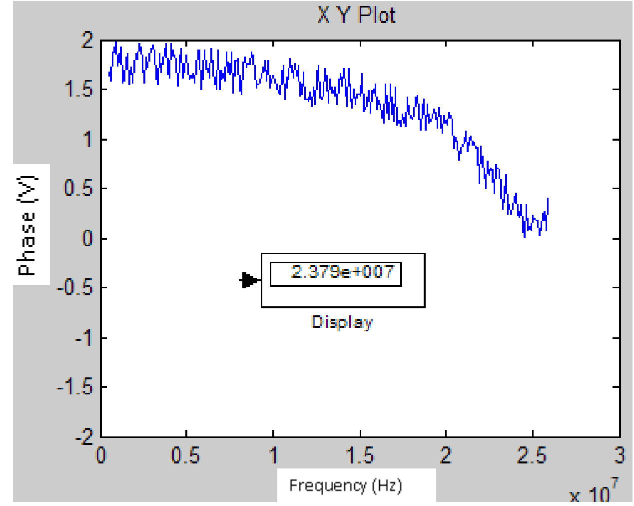

Figure 25 Phase vs. Frequency with noise and low *Q*, high upper hybrid plasma frequency. The display shows the averaged upper hybrid plasma frequency. Actual is 25 MHz.

The next factor to test is the quality factor, *Q*. Through a concept similar to that which was discussed with the high frequencies in the last paragraph, the higher quality factors result in values closer to the actual upper hybrid frequencies. It is interesting to note in Figure 26 that the lower frequency when combined with the low *Q* results in a higher averaged frequency. This, when combined with the higher frequencies above, shows that where the actual upper hybrid frequency is relative to the frequencies that are being swept through determines whether the estimated value will be high or low. A frequency lower in the scale is likely to be estimated high, while one higher in the scale is likely to be estimated low, as shown by the differences in Figures 25 and 26. However, a high quality factor still counteracts this, as shown by the higher quality factors in Figure 26. This same high quality factor could possibly result in the sampler missing the notch.

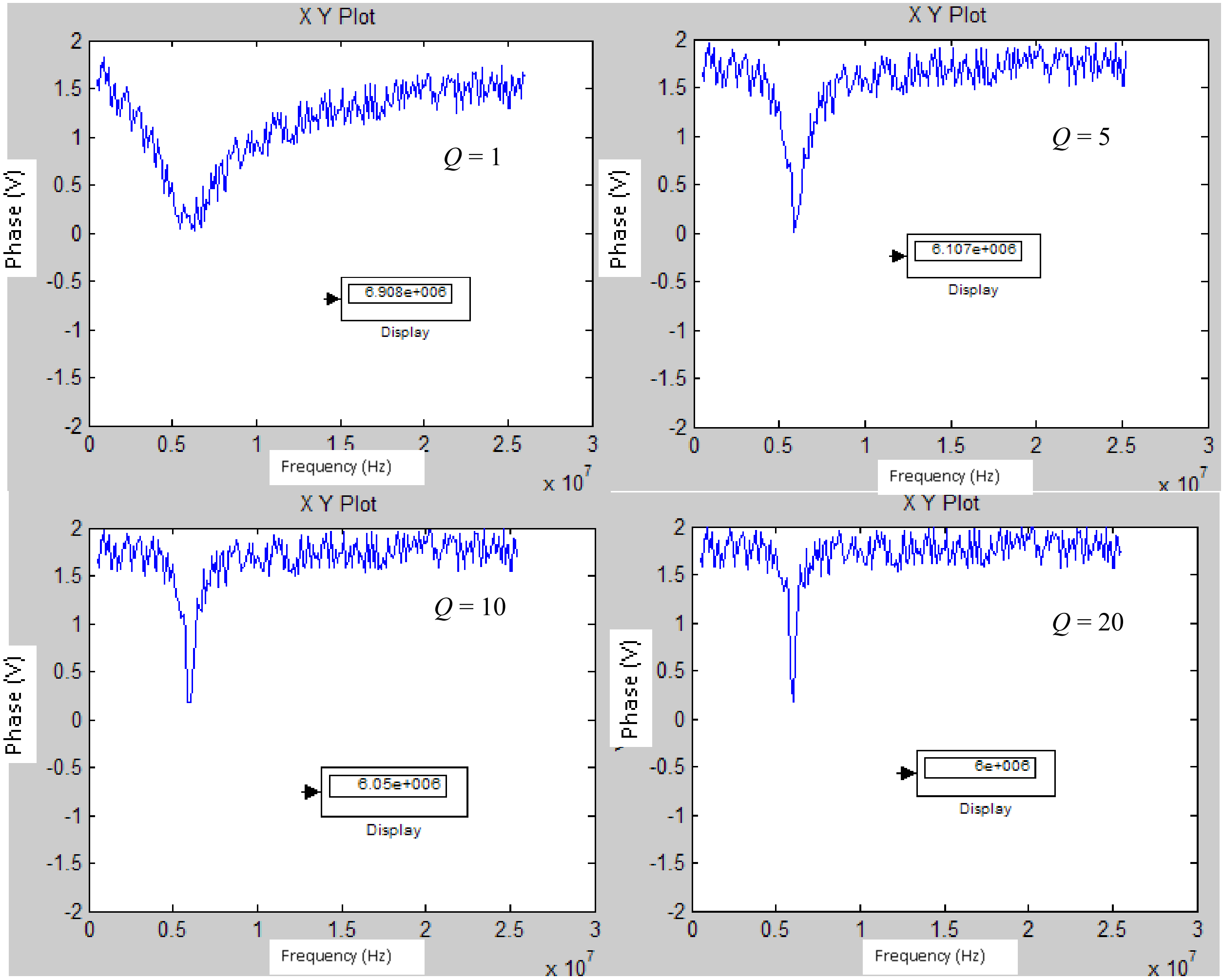

Figure 26 Phase vs. Frequency with noise, with display of averaged upper hybrid frequency. Upper hybrid frequency is held constant at 6 MHz, noise is held constant at 25%, and compared voltage is held constant at 0.9 volts. The quality factor is varied.

The compared voltage (voltage under which values being to be averaged) is the next parameter investigated. It can be thought of as the value under which frequencies can be considered “interesting.” Inspection of Figure 27 suggests that this value is surprisingly unimportant. However, this can be deceptive as the quality factor is relatively high. As shown in Figure 28, with a low quality factor, we can see the importance of a low compared voltage. In general, a lower compared voltage results in a better averaged frequency. This is because fewer frequencies will be included in the average, and the lower voltage values are more likely to be closer to the actual upper hybrid plasma frequency. However, it should be noted that making the value too low with a high quality factor, high noise, or low sampling rate can result in completely missing the frequencies to be averaged. Therefore, the upper hybrid plasma frequency can still be determined in spite of low quality factor by using a low compared voltage.

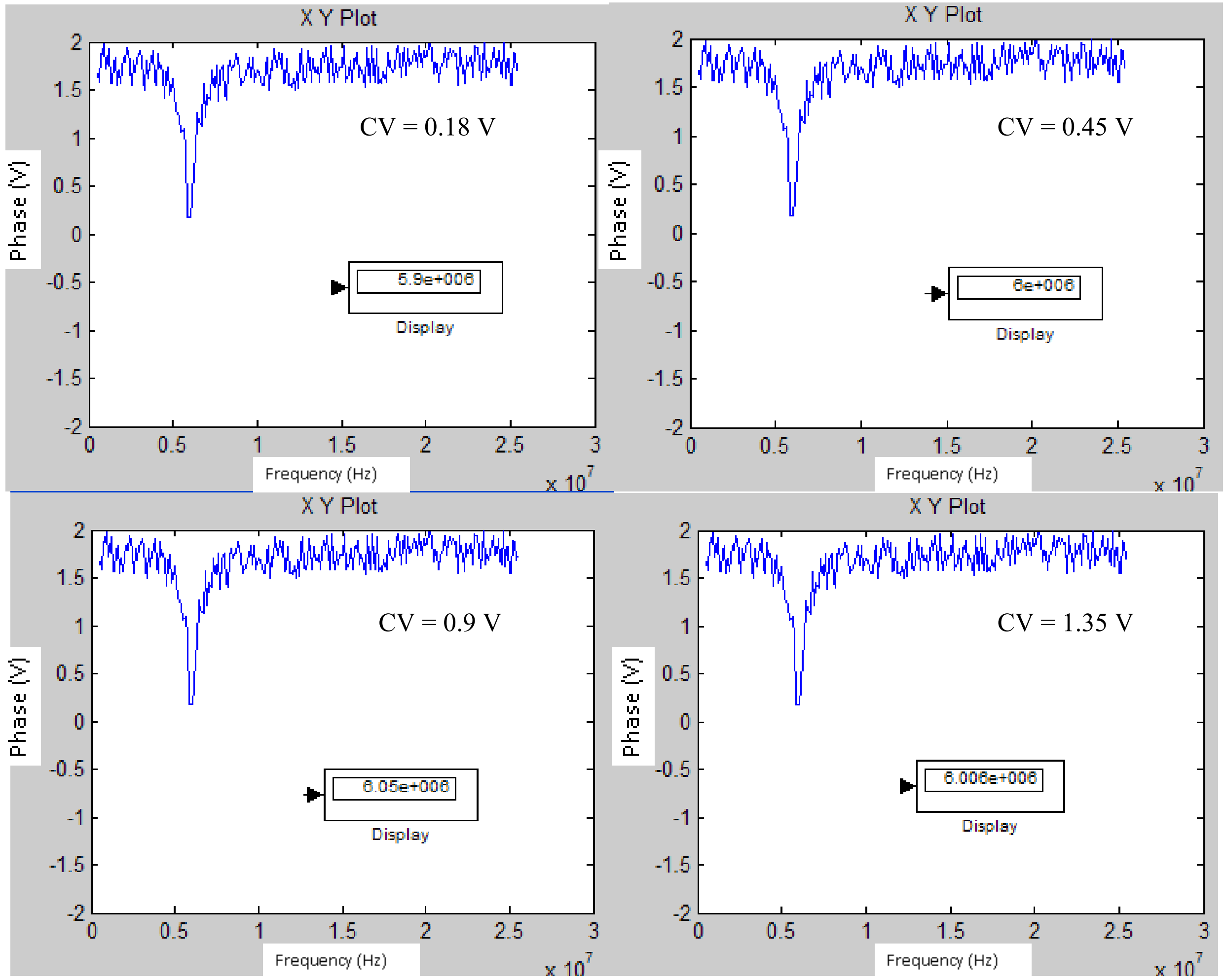

Figure 27 Phase vs. Frequency with noise, with display of averaged upper hybrid frequency. Upper hybrid frequency is held constant at 6 MHz, noise is held constant at 25%, and *Q* is held constant at 10. The compared voltage (CV) is varied.

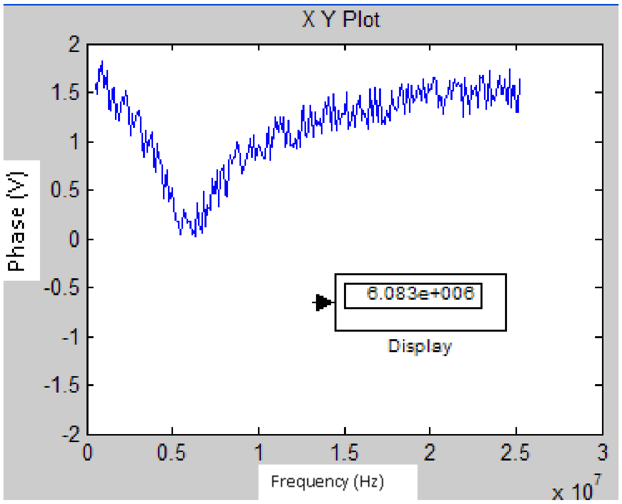

Figure 28 Phase vs. Frequency with noise and low *Q* (1), low compared voltage (0.18 V). The display shows the averaged upper hybrid plasma frequency. Actual is 6 MHz. The result is much better than in Figure 26.

Finally, the error percentage itself will be examined. As expected, with more noise you get more error. What is interesting, conversely, is that the upper hybrid frequency is not completely lost until the noise strength is plus or minus 0.9 V. Not coincidentally, this is the compared voltage. For high quality factor, until the noise is large enough to take an “uninteresting” frequency below the compared voltage, it will not be averaged and therefore does not affect the outcome. It is only the part of the noise that is subtracted from the signal outside of the interesting frequency range that matters, as anything added to it will still result in it being ignored by the compared voltage. While added voltage can cause you to lose “interesting” frequencies, as it can make it larger than the compared voltage, there hopefully will be enough samples that the averaging will take care of outliers. This makes the method surprisingly robust. Until the noise is on the level of maximum voltage (1.8 V) minus the compared voltage (in this case 0.9 V), it will only slightly affect the averaged frequency, and thus it is still possible to get an accurate estimate at the upper hybrid plasma frequency.

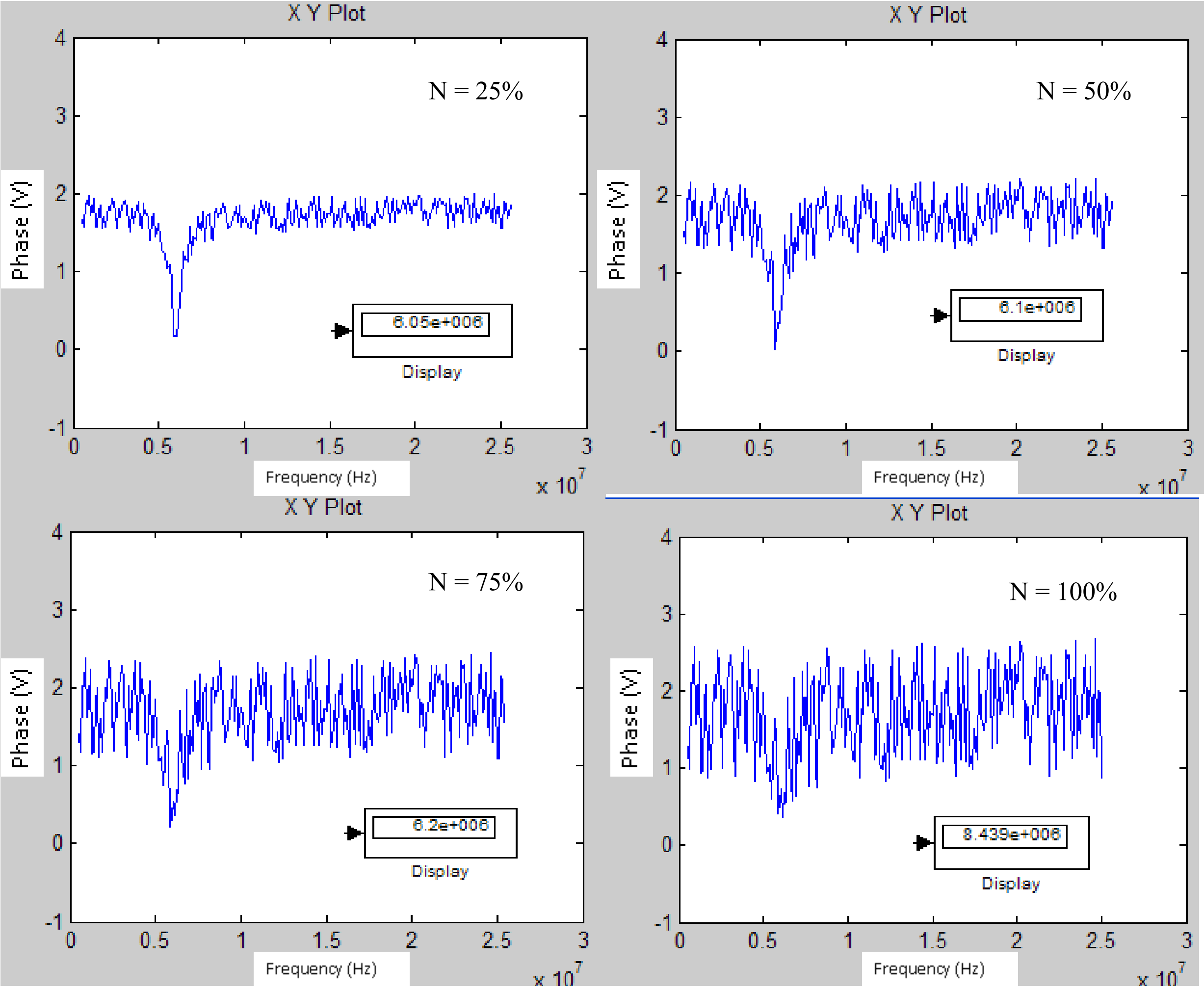

Figure 29 Phase vs. Frequency with noise, with display of averaged upper hybrid frequency. Upper hybrid frequency is held constant at 6 MHz, compared voltage is held constant at 0.9 V, and *Q* is held constant at 10. The noise magnitude (N) is varied.

In summary, all four factors must be considered. The original upper hybrid plasma frequency is the least important of the factors. However, the larger the spectrum of frequencies swept, the more accurate the test, especially for lower quality factors. Ideally, the upper hybrid plasma frequency will be somewhere between the lower end of the spectrum and the middle. Quality factor, noise level, and compared voltage are all interconnected. Higher quality factors and lower noise levels are ideal, but in less favorable conditions a low compared voltage can make up for other conditions deficiencies. However, it must be remembered that enough samples must be collected to average. This means that quality factor must not be too high for low sampling frequencies, and the compared voltage cannot be too low. Otherwise, it is possible to get no samples within the “interesting” frequency range, resulting in no data.

Chapter 5 Conclusions and Future Work

Plasmas can have large affects on communications within our ionosphere. Therefore, it is important to study the ionosphere and characterize the properties of the plasma therein in order to understand the affect on communications, and determine how to mitigate the “plasma interference” effects. Accordingly, a joint effort between OSIRIS and Arecibo was enacted in order to better understand how heating the ionosphere will influence the plasma characteristics. OSIRIS instrumentation will include the PFP, which is an effective tool for determining plasma density. Signals transmitted into a plasma will experience a phase shift. By determining when the phase shift is zero, one can determine the upper hybrid plasma frequency and subsequently derive the plasma density.

The simulations have shown the AD8302-based phase detector PFP is a viable system. The phase shift does go through zero at the upper hybrid plasma frequency, and it is also here that the gain due to the plasma is at a maximum. The quality factor ideally would be low in order to gain resolution on how the phase shift changes with frequency. The antenna’s inherent parameters should not prevent the PFP from being able to determine the plasma parameters. Finally, the AD8302 phase detector can adequately determine the phase shift and gain of the plasma.

By finding the upper hybrid plasma frequency through simulations, we were able to determine the influence of four factors in determining the upper hybrid frequency. Higher frequencies and frequencies near the edges of the swept spectrum produce poor results. Quality factor, noise level, and compared voltage all affect quality and accuracy. High quality factor and low noise are ideal for finding the upper hybrid frequency, but in the absence of ideal conditions the compared voltage level can be lowered in order to yield more accurate results. This apparent contradiction from the AD8302 phase detector model in which a low quality factor is preferred can be explained as follows. A high sample rate allows for enough samples to still be taken within the tighter notch of a high quality factor, and this would allow enough frequencies to be within the range to be averaged. However, a low sample rate with high quality factor can still result in loss of samples, especially with a low compared voltage, as noise could take the few samples obtained outside of the voltage range that signifies frequencies to be averaged. This can result in a complete loss of the upper hybrid plasma frequency.

In the future, the operational testing of the prototype PFP must be conducted to enable model verification. The OSIRIS mission, in coordination with Arecibo, will provide an initial opportunity to conduct the appropriate operational tests to physically measure the effects of ionospheric heating on plasma characteristics, how they affect communications, and verify the model.

References

Atmospheric Sciences Research, "Glossary of Terms – atmosphere" [online] http://asd-www.larc.nasa.gov/asd_over/glossary/a.html, NASA Langley Research Center, October 1, 2002.

Bilén, Sven G., Pavol Pribula, Allen T. Kummer, Adam C. Escobar, Julio V. Urbina, Paul A. Bernhardt, Michael T. Rietveld, Michael J. Kosch, and Sixto A. Gonzalez, "The OSIRIS CubeSat Mission: A System of Satellites for Investigating the Response of the Stimulated Ionosphere," 2009 AGU Fall Meeting, San Francisco, California, 14–18 December 2009.

Carlson, Chad. 2004. Next Generation Plasma Frequency Probe Instrumentation Technique. Masters Thesis, University of Utah, Logan.

Chen, Francis F. 2006. Introduction to Plasma Physics and Controlled Fusion. 2nd ed. New York: Springer Science and Business Media.

Kummer, Allen T., Sven G. Bilén, Richard T. Fissinger, and Brian A. Herrold, "The Hybird Plasma Probe: A unique combination for plasma probes for in situ space environment characterization," 19th ESA Symposium on Rocket and Balloon Programmes, Bad Reichenhall, Germany, 7–11 June 2009.

Siegel, Robert. 2004. Design of a Hybrid Plasma Probe System. Masters Thesis, The Pennsylvania State University, University Park.

Swensen, Charles. 1989. An Evaluation of the Plasma Frequency Probe. Masters Thesis, University of Utah, Logan.

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