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# Steerable Antenna Solution for Communication between Cars

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Master of Science in Electronics
Submission date: June 2007
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## Problem Description

Q-Free and SINTEF are partners in an EU-project where communication between cars, and between cars and base stations along the roads, is a central part. Initially an antenna that is omni directional is used, but we see a great need to introduce solutions where the radiation direction can be steered. By this the radiated effect can be focused in the preferred direction and the range of the system can be increased. In this assignment we wish to begin the development of a steerable antenna that is to lead to a prototype that can be used in field testing. The antenna solution consists of an RF-fed monopole surrounded by passive parasitic monopoles. This is called an Electrically Steerable Passive Array Radiator or an ESPAR antenna. The passive monopoles are connected to the ground plane by a switch, and by controlling this switch the parasitic monopoles are either shorted or open circuit. The different loads lead to that the parasitic monopoles, by coupling, affects the antennas radiation patterns. In a more advanced form different reactive loads are switched in. The assignment will consist of three parts. A theoretical study, a design part and a production and testing part. It will be possible to use WIPL-D for the simulations on the radiation characteristics according to the setting of the switches.

Assignment given: 15. January 2007
Supervisor: Jon Anders Langen Aas, IET

# Preface

This is the thesis for the completion of my master's degree in electronics from the Norwegian University of Technology and Science (NTNU). This thesis was written in the spring of 2007 and is the last part of a five year program at the Department of Electronics and Telecommunications.

The thesis is written for SINTEF IKT in Trondheim as a part of a project concerning communications between cars. I would like to thank Irene Jensen from SINTEF IKT and Jon Anders Aas from NTNU for their valuable help and guidance on completing this project. I would also forward thanks to "Teleteknisk verksted" at NTNU for the excellent physical construction of the designed antenna.

# Summary


This thesis describes the work on designing and testing an antenna solution for communications between cars. The antenna that is to be used is a so called ESPAR antenna or Electronically Steerable Passive Array Radiator using monopoles over a circular ground plane.

Simulations were made on the following variations of the antenna:

- The number of passive monopoles and the angle between them
- The radius and height of the active and passive monopoles
- The height of the skirt and the radius of the ground plane
- Matching schemes

The antenna that was decided to be the best for this application had these characteristics:

- Ground plane radius 75 mm or half a wavelength
- Skirt height of 37.5 mm or a quarter wavelengths
- Six parasitic monopoles with a height of 39 mm equally spaced around an active monopole of 35 mm
- Distance from active monopole to parasitic monopoles of a quarter wavelengths
- Half power beam width of about 90 degrees and a front to back ratio of 16 dB
- Gain of about 7.5 dB and an elevation angle of 25 degrees

From these results a prototype of the antenna was constructed with different heights of the active and parasitic monopoles. The measurements showed less variation between the different configurations of the antenna than the simulations indicated. The largest difference was the elevation angle of the antenna. This was found to be about 0 degrees for all configurations which is an improvement of about 25 degrees from the simulated results. The best results was found to be with an antenna that has the same configurations as the simulated one described above but with a parasitic monopole height of 37 mm.

The measurements showed the following specifications:

- Gain of about 9.5 dB
- HPBW of 80 degrees
- FTBR of about 12 dB

Because of certain elements in the construction of the antenna, the measurements of the matching were inconclusive, and were not weighed heavily in this thesis.

# 1 Introduction

This thesis will present the work on designing a so called ESPAR antenna. ESPAR stands for Electronically Steerable Passive Array Radiator and can consist of many different types of antennas in different kind of arrays. In this thesis monopole antennas over a circular ground plane will be explored. The main application of this antenna is communications between cars. In the last years more and more high-tech equipment have been added to the cars. Not only for adding luxury to the cars, but also for safety reasons. One safety measure is for the cars to communicate between each other. This can be used to mediate information of the traffic situation from one car to another, for instance on accidents or road work. Another application is to have transmitters that transmit different kinds of information placed on the roadside. This can be information on for instance speed limits and dangerous turns.

To implement this, an antenna that can be steered in different directions is needed. This to ensure that the number of transmitters that potentially are on a busy road do not interfere with each other. It is also a measure to reduce the power consumption. An ESPAR antenna is a good solution for this since it contains no movable part and is often cheap and easy to implement. The antenna is thought to operate at about 5 GHz. But for this frequency the dimensions of the antenna are very small and the chance for mistakes in the construction of the antenna is large. For this reason the antenna will be designed for a frequency of about 2 GHz. This makes the antenna more than twice as large and it gets easier to build and measure on.

The requirements for this antenna include:

- Narrow beam width, maybe as low as 60 degrees
- Direction steer able in, at least, between front, sides and backwards directions
- Elevation angle of maximum radiation in the vertical direction

- Possibility to have an omnidirectional configuration in addition to the steer able configuration
- At least a 10 % impedance bandwidth

First some previously published work that is particulary important for this thesis will be presented. Then the different possible configurations of the antenna will be simulated, before testing is accomplished on a protoype of the antenna. The thesis will not stribe to decide which configuration that in the end is the best because this can vary with further requirements. But some antenna structures will be explored more carefully because they exhibit properties that are generally prefferable.

# 2 Previously published work

An ESPAR antenna is a good way of reducing the power consumption of an antenna system by increasing the gain in the desired directions and thus also to avoid interference between different transmitters. Because of this, quite a lot of previous research has been made on this type of antenna. Some previous research, that is particularly relevant for the investigations that are going to be made in this thesis, will be presented in this chapter. Only results from antennas using monopoles over a circular ground are going to be presented.

In 2005 Kawakami and Ohira published an article concerning this type of antenna and different measures to improve the characteristics of the antenna. [1] Their investigation concerned an ESPAR antenna with a circular ground plane and monopoles as radiators, reflectors and directors. Their main concern was the shape and size of the ground plane. They discovered that by using a ground plane with a radius of 0.5 wavelengths and adding a skirt around the edge of the ground plane they could lower the elevation angle of the maximum radiation of the antenna. This is important for the investigations that are going to be made in this text. The ideal length of the skirt was found to be about 0.25 wavelengths. By doing this they obtained an elevation angel of about 5-10 degrees above the ground plane. [1]

Since the antenna that will be constructed in this text is going to be used for communications between cars, and it is important to have a low elevation angel, the results of Kawakami and Ohira are important for the further investigations.

It is possible to load the parasitic monopoles with reactive elements to help steer the radiation and to change the matching of the monopoles. This has been investigated by Janapsatya and Bialkowski of the National University of Queensland. [2] They discovered that by loading the elements correctly they could steer the radiation in 36 discrete steps with ten degrees spacing instead of the initial 6 steps with 60 degrees spacing. They also obtained an increase in gain of about 0.5 dB. These characteristics will not be investigated in this text and is just mentioned as background information.

There have also been made investigations on the effect of making this type of antenna a dual-band antenna. By using a double set of parasitic monopoles an antenna that can be used for two different frequencies was proposed by Shibita and Tomoshige in 2005. [3] Their investigations indicate that this can be done with good results if required.

# 3 Simulations in WIPL-D

WIPL-D is a high frequency electromagnetic modeling and simulation software that employs the method of moment [4] for calculations. This makes this program rapid to calculate the results, with fairly good accuracy. WIPL-D was originally designed by Prof. Dr. Branko Kolundzija with the University of Belgrade, and has been further developed and commercialized over the years. [5] This software is mainly going to be used for initial comparisons and in that way find a temporary solution to investigate further in a more complex simulation tool.

Firstly simulations on the number, and the angular spacing of the connected monopoles will be performed. Subsequently simulations of the different parameters of the antenna, such as length and width of the monopoles and height of the skirt will be run. Lastly the text will describe more thoroughly the situation that is considered the so far best solution. In the situations where a VSWR diagram and Smith-chart appear in pairs the points on the curves are for the same frequencies. All the matching figures in this chapter have a frequency range from 1.5 GHz to 2.5 GHz with steps of 100 MHz.

## 3.1 Investigation of active monopole at the center of a circular ground plane

This section will consider simulations in WIPL-D of the mentioned Electronically Steer able Passive Array Radiator (ESPAR) with a center active monopole. The simulations will be performed with a circular ground plane with a radius of 0.5λ, and a skirt of length 0.25λ, as shown in Figure 1. The number and placement of the parasitic monopoles will be varied. The reason for the implementation of the skirt before the effects of this is simulated, is that it is considered a measure that, according to Kawakami and Ohira [1], only has positive effects. The effects of the length of the skirt will be discussed in section 3.2.4. The height of the parasitic monopoles in this section is set to a quarter wavelength or 33 mm, based on previously published work. The radius of the monopoles is 2 mm. The effect of the height and diameter of the monopoles will be discussed in 3.2.1 and 3.2.2.

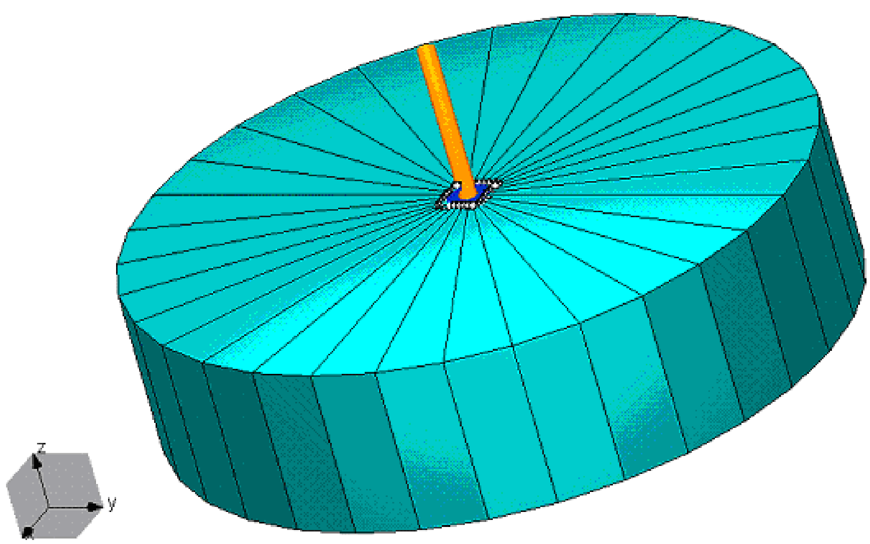


**Figure 1 Illustration of model**

### 3.1.1 Matching of the center monopole

The first thing that is going to be investigated is the matching of the single active monopole to a 50 Ohm reference.

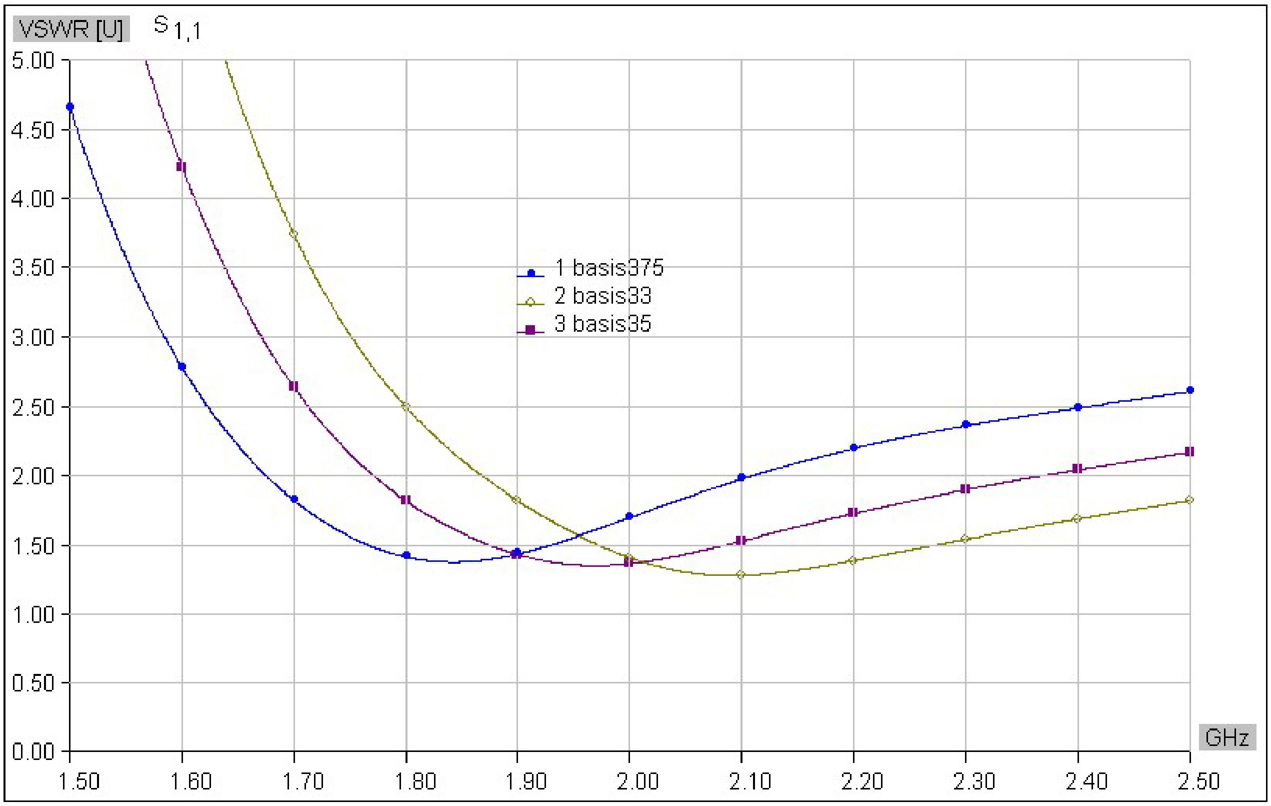


**Figure 2 Matching of the center monopole**

As can be seen from Figure 2 the matching to 2.0 GHz is best for the length of 35 mm, which is expected since the electrical length often is longer than the physical length because of end effects. [4] Therefore the length of this monopole is set to 35 mm for the rest of chapter 3.

### 3.1.2 Exploration on the effect of unconnected monopoles

By placing monopoles in a circle with an individual angular spacing of ten degrees, and each with a distance of 0.25λ from the active monopole, a worst case scenario is produced. See Figure 3 for illustration. This is done to investigate what effect the unconnected monopoles have on the antenna and to test the prospect of simplifying the model.

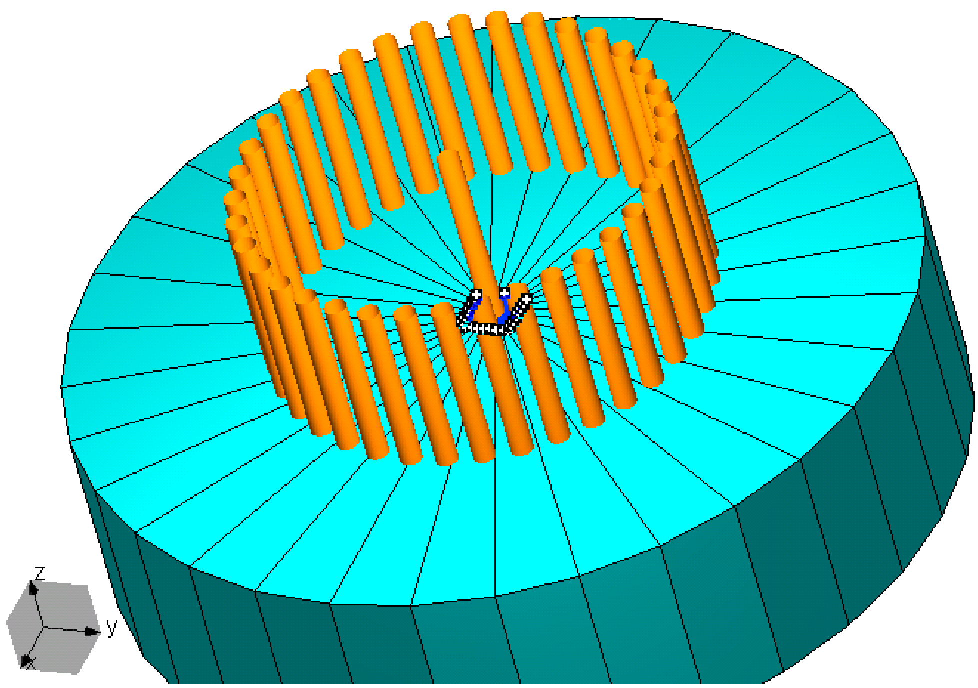


**Figure 3 Illustration of full plane situation**

The radiation characteristics in the xz-plane, or the elevation plane, are shown in Figure 4, both for the full plane (blue) situation and for the single monopole situation. One can observe that a small loss in gain is present and a small decrease in the angle of maximum radiation when the unconnected monopoles are added. The differences are however sufficiently small so that these effects can be ignored for most cases. This result in that further exploration of this configuration will be performed with no unconnected monopoles at the opposite side of the connected monopoles.

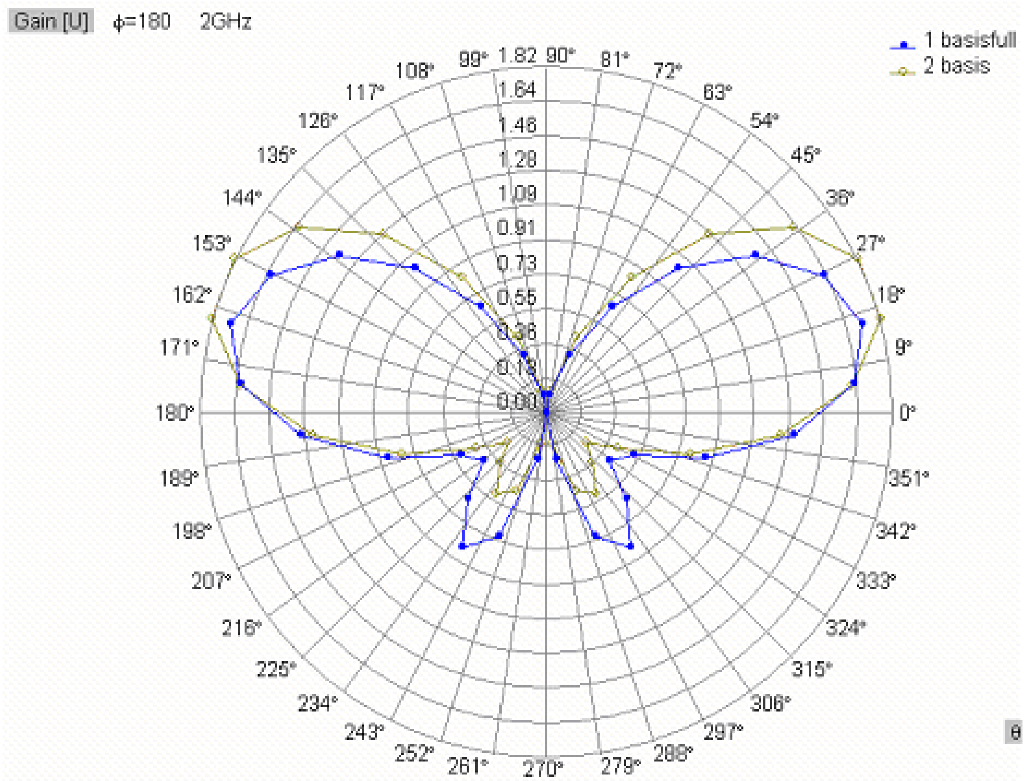


**Figure 4 Radiation characteristics for full plane situation and single monopole situation. The gains are shown in a linear scale**

This will simplify future work with this antenna. The testing will be performed with all the parasitic monopoles present, but for the simulation work these will be ignored.

### 3.1.3 Case with two parasitic monopoles

In the following sections the different cases of two, three, four and five connected parasitic monopoles will be discussed. The legends in the figures are descriptive for how many parasitic monopoles there are and how many degrees there are between each of them. For instance the legend "3mon50grad" describes a situation with three parasitic monopoles each spaced 50 degrees apart. The half power beam widths and elevation angels of the different cases will be discussed in section **Error! Reference source not found.**3.1.7.

The first simulations are completed with to parasitic monopoles placed on a circle with a radius of 0.25λ with increasing angle between the two monopoles. Illustration is shown in Figure 5.

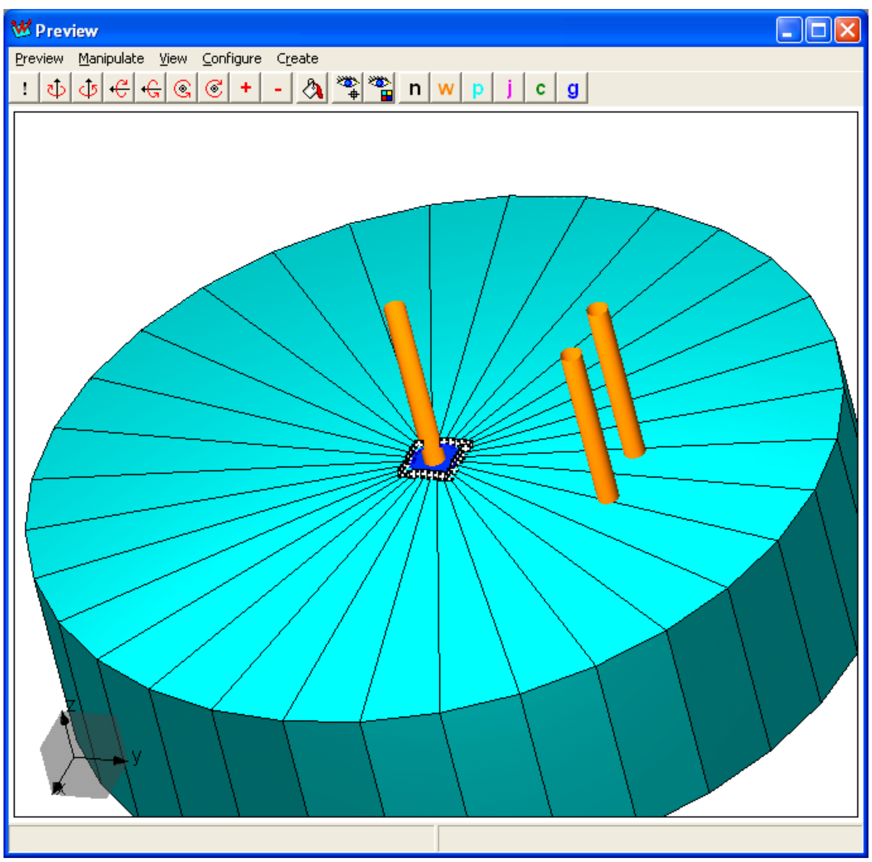


**Figure 5 Illustration of the two monopoles model**

From Figure 6 and Figure 7 one can observe that the matching of the antenna to a 50 Ohm reference gets worse with increasing angle between the two monopoles. Even at the lowest angels described in this text, the voltage standing wave ratio is too high according to the desired specifications of a VSWR below 2. This can be mended by a matching scheme. Some measures to get the matching better will be discussed in section 4.3.

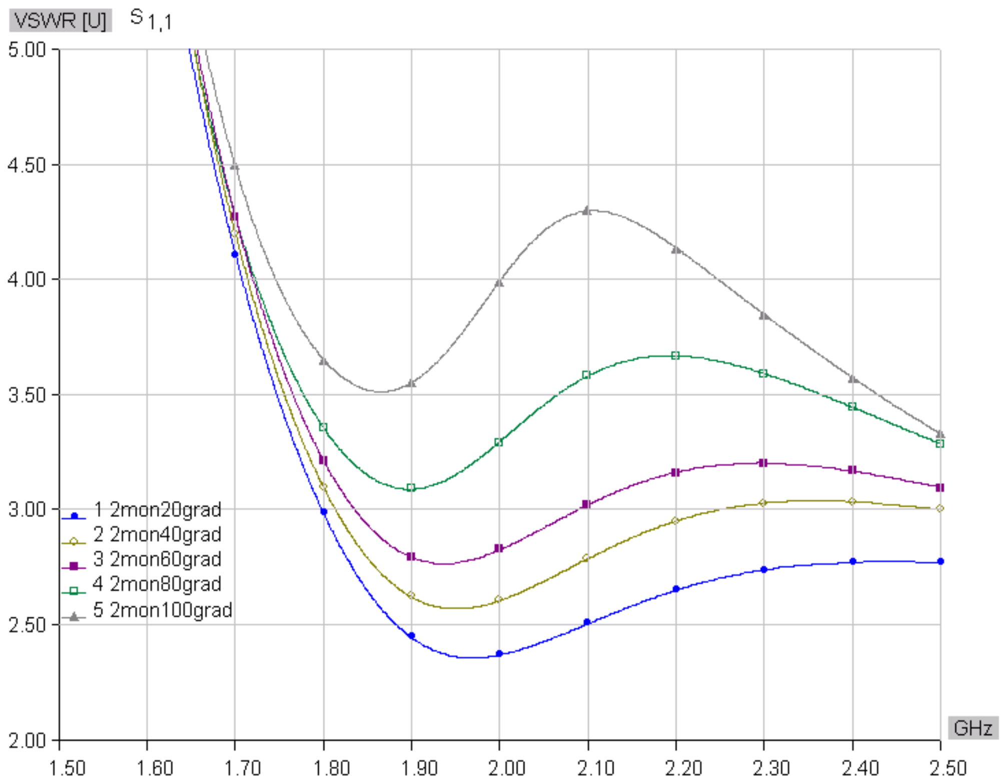


**Figure 6 VSWR for the different cases with two monopoles**

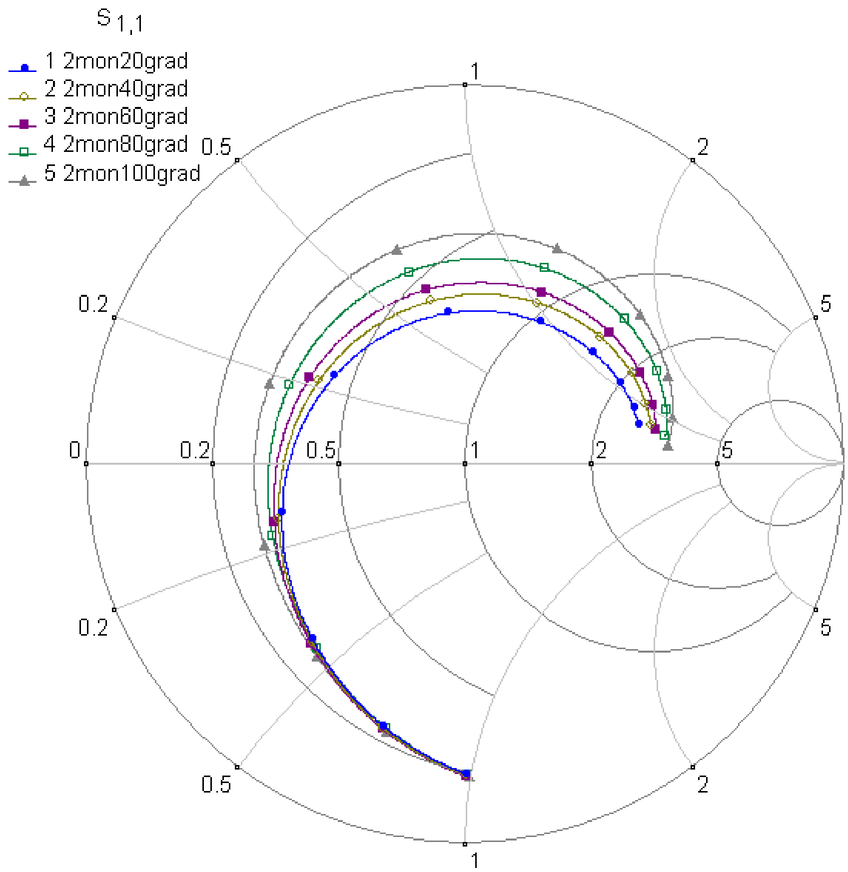


**Figure 7 Smith chart for the different cases**

As can be seen from the smith chart in Figure 7 the matching characteristics for the different schemes follow much the same course. But the further apart the monopoles stand the more inductive the antenna becomes.

## Radiation patterns

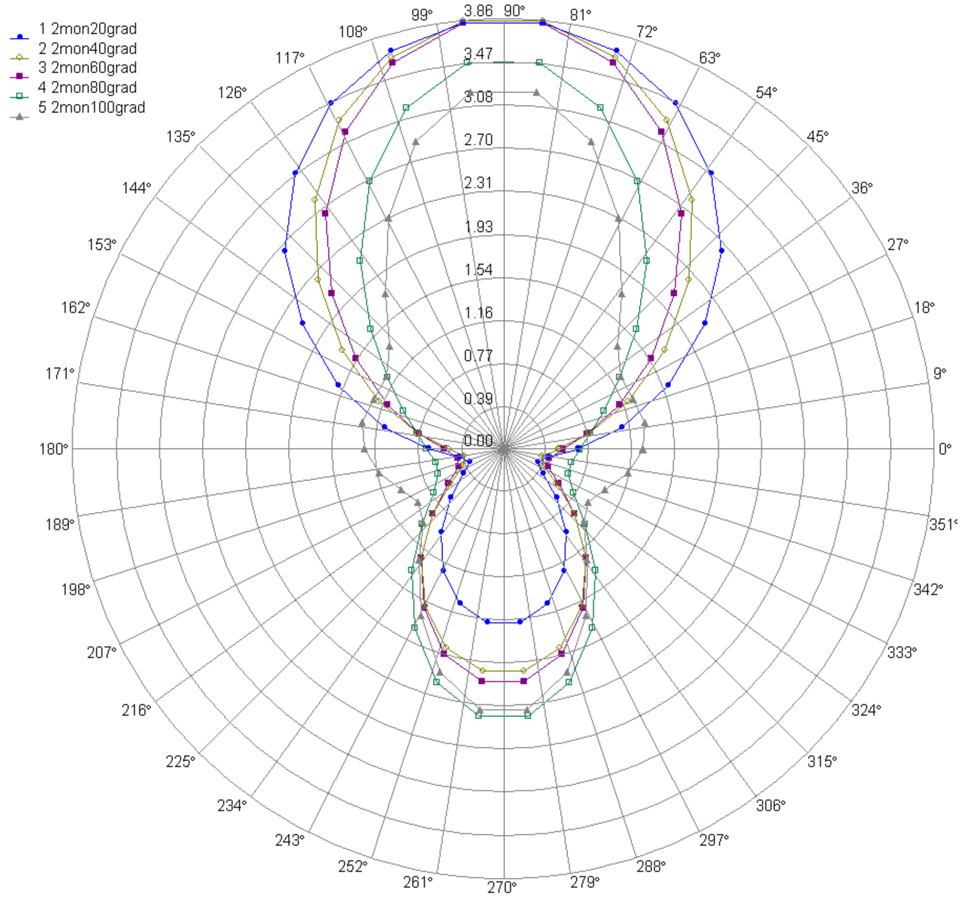


**Figure 8 Azimuth-radiation for different angels (linear scale)**

It is observed in Figure 8 that the larger the angle is between the two monopoles, the narrower the HPBW becomes. But for angels larger then about 60 degrees, a loss of gain is observed. The loss in gain results in a greater backwards radiation. This shows that it is reasonable to assume that for reflectors that is positioned more than 60 degrees apart lets too much of the radiation slip trough between them. But it can also be seen that the beam width decrease all the way, such that 60 degrees spacing seems to be the best solution, at least for the two monopoles case.

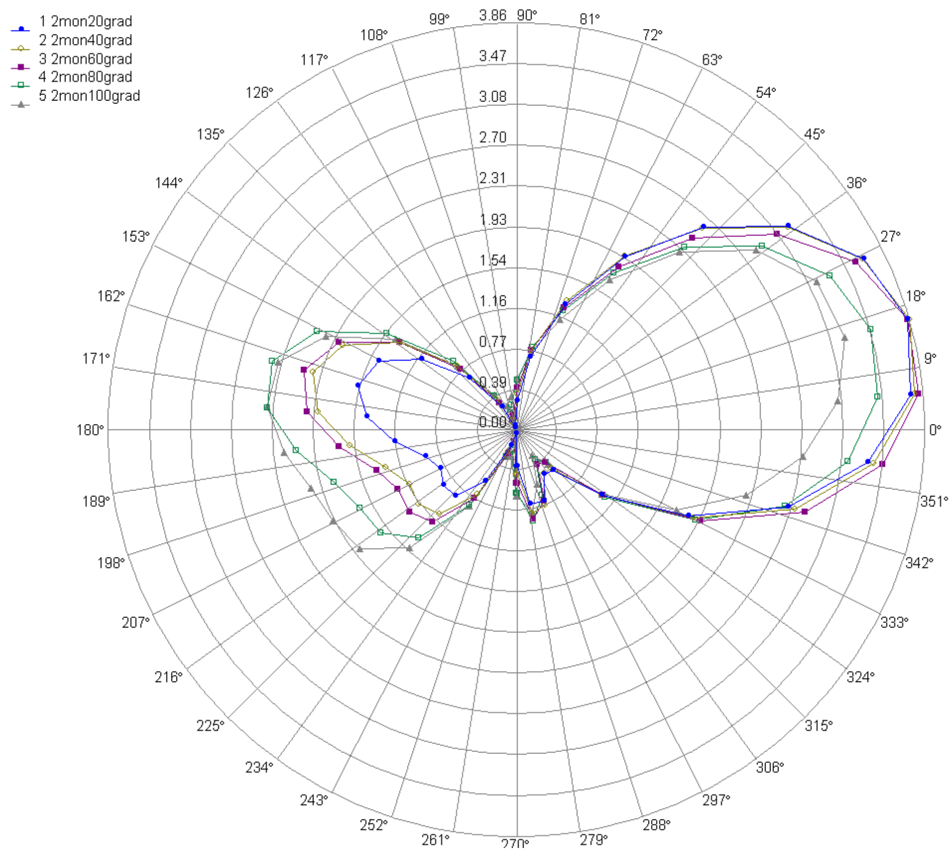


**Figure 9 Elevation radiation pattern (linear scale)**

From Figure 9, one can observe that the angle of maximum gain is constant for all cases. The gain however behaves in about the same way as for the azimuth radiation pattern. That is the gain decreases with an angle between the two monopoles larger than 60 degrees. By this it can be concluded that the spacing of the monopoles doesn't affect the elevation angel of the radiation, but it affects the gain and half power beam width. A summary of the different properties of the configurations presented in this section is given in Table 1.

### 3.1.4 Three parasitic monopoles

In this section the same characteristics will be explored for three connected monopoles as for the two monopole case. As can be observed from Figure 10, the three monopoles case exhibits much of the same matching characteristics as the two monopoles case. The larger the angle, the poorer the matching becomes. As for the two monopole case, this situation also has the problem with high degrees of mismatching. It is expected that these problems can be corrected by different matching schemes which will be discussed in section 4.3.

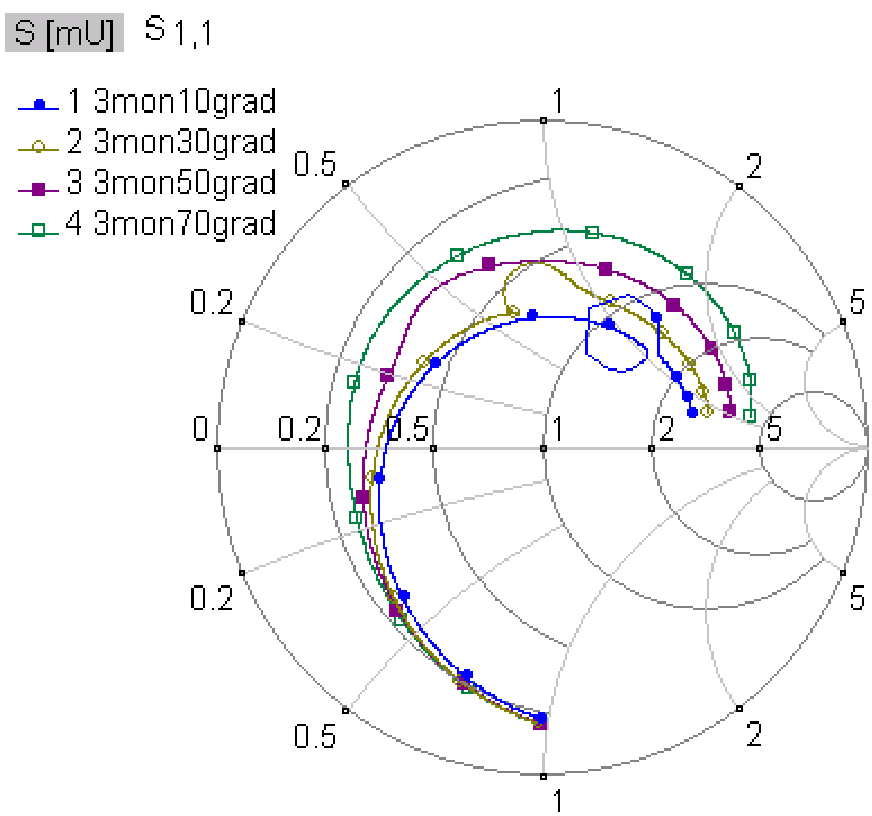


**Figure 10 Smith chart for the three monopole case**

## Radiation patterns

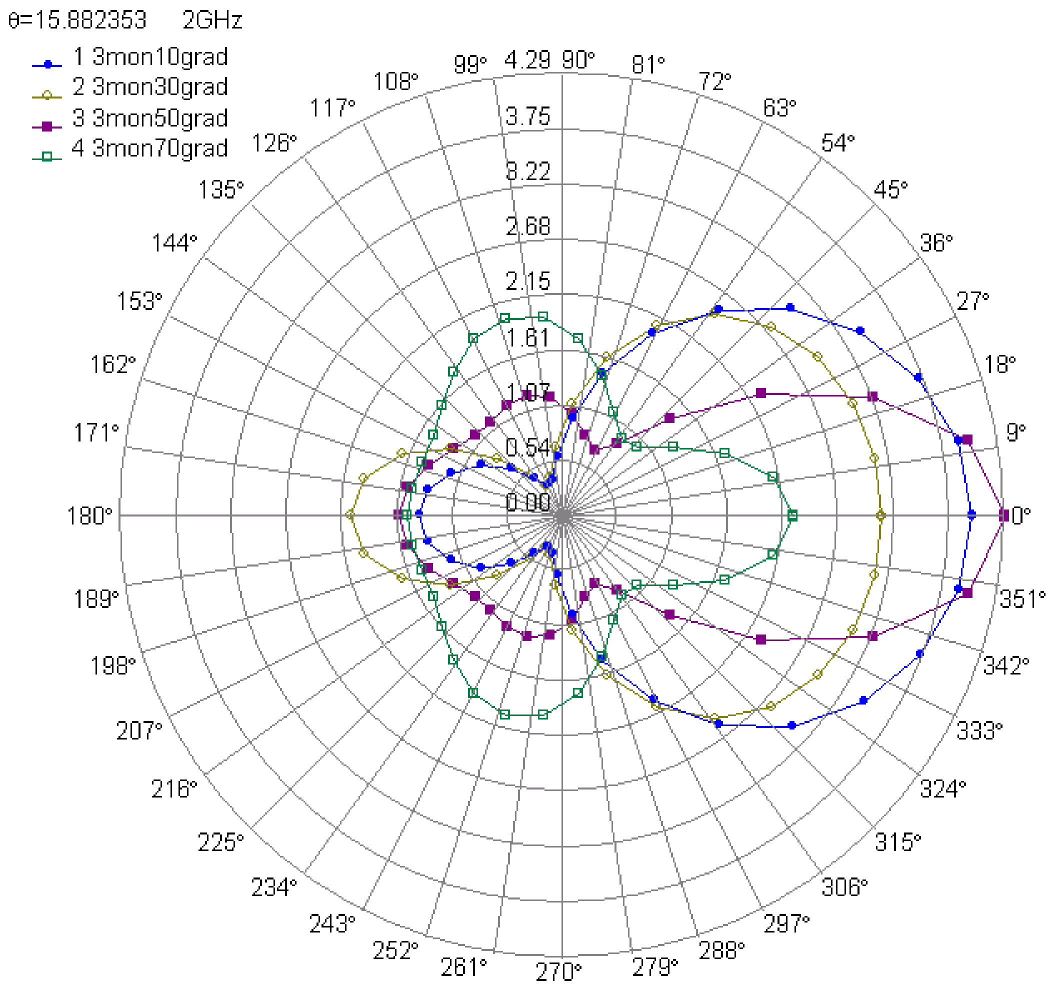


**Figure 11 Azimuth radiation pattern for three parasitic monopoles (linear scale)**

From Figure 11 and Figure 12 one can extract that the larger the angle between the monopoles are, the more directive the radiation becomes. However one negative effect occurs for certain angles. The gain is significantly lower for the 30 and 70 degrees cases than for the 10 and 50 degrees cases. And one can observe that most of the lost radiation leaks sideways. More cases are summarized in Table 1.

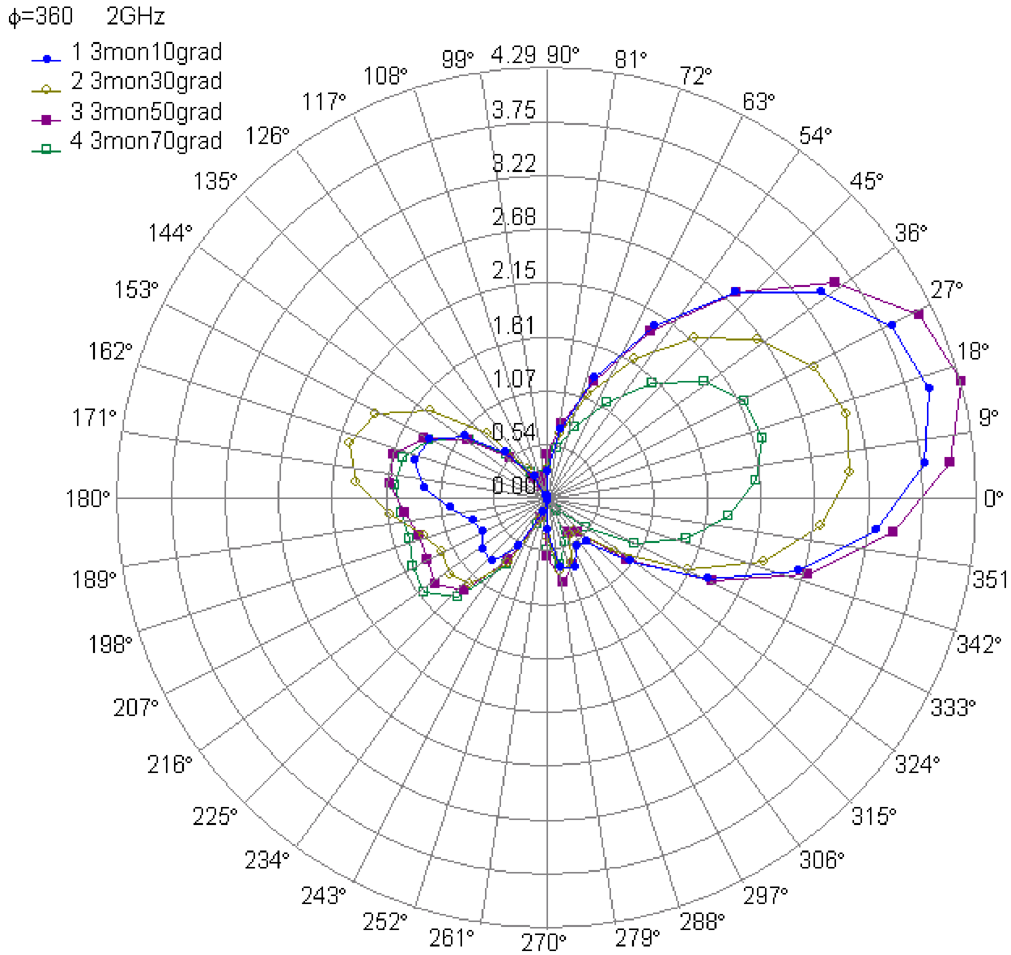


**Figure 12 Elevation radiation pattern for three parasitic monopoles (linear scale)**

At this stage of the work an important discovery is made. The antenna was discovered to exhibit better properties for 2.1 GHz than for 2.0GHz. The reason for this is not yet known. It could be that the distance from the active monopole to the parasitic monopoles is a factor, but it is considered that the main reason for this is a mismatch of the length of the different monopoles. This will be investigated further in 3.2.2. For the time being the frequency is simply raised to 2.1 GHz to compensate for this mismatch. As seen in Figure 13, this adjustment gives much better characteristics. The gain increases for the narrower beams which is preferred in this case. The sideways radiation is also decreased.

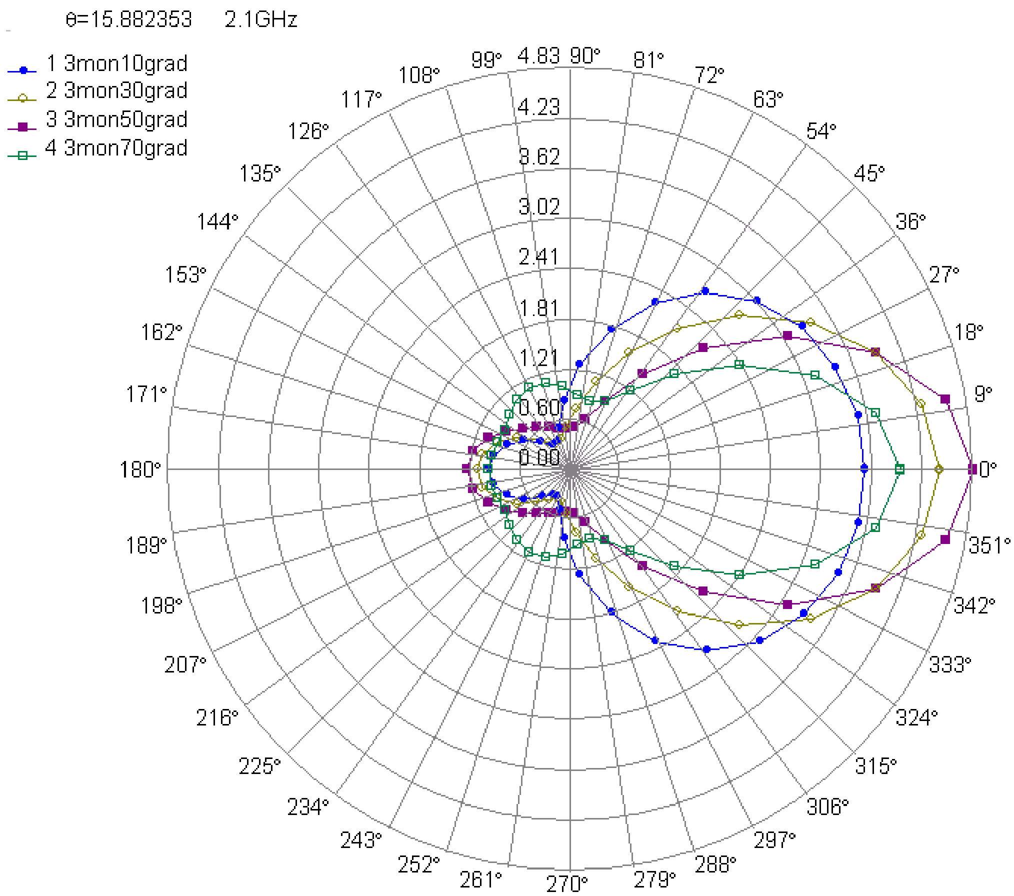


**Figure 13 Azimuth radiation pattern for the increased frequency case (linear scale)**

### 3.1.5 Four parasitic monopoles

Again, in this section the same distance between the active monopole and the parasitic is used, since the parasitic monopoles still will be used as reflectors.

Figure 14 shows the matching characteristics for the different cases with four parasitic monopoles. The same effect as for two and three monopoles is observed here. The wider apart the monopoles are placed the worse the matching becomes.

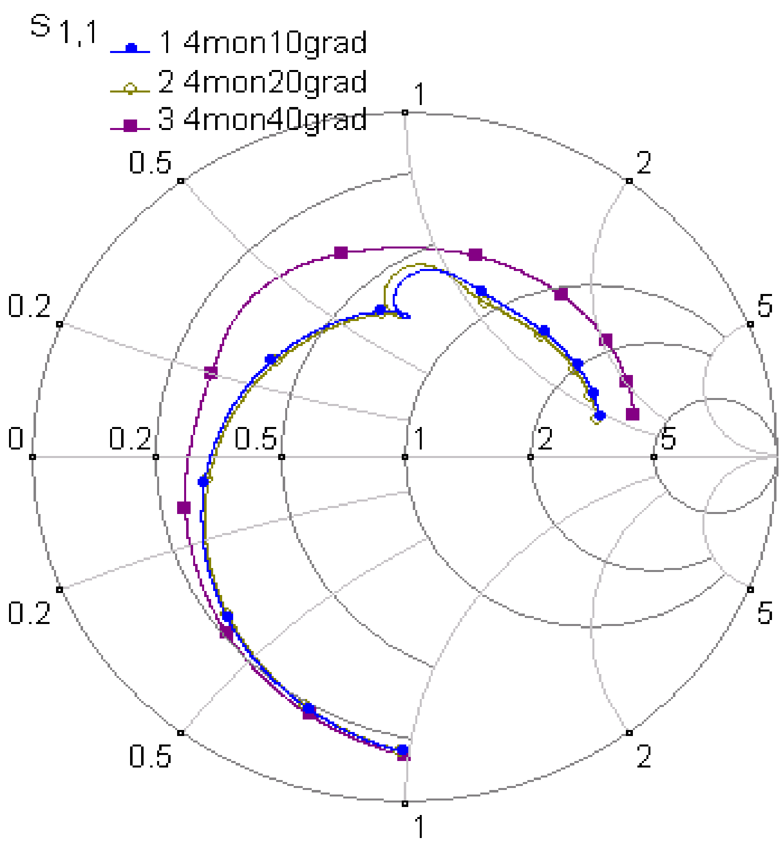


**Figure 14 Smith Chart for the four monopoles case**

## Radiation patterns

As discussed in the previous section the antenna exhibits better characteristics with a slightly higher frequency than the frequency it is designed for. Because of this, the rest of this section (3.1) the frequency will be set to 2.1 GHz.

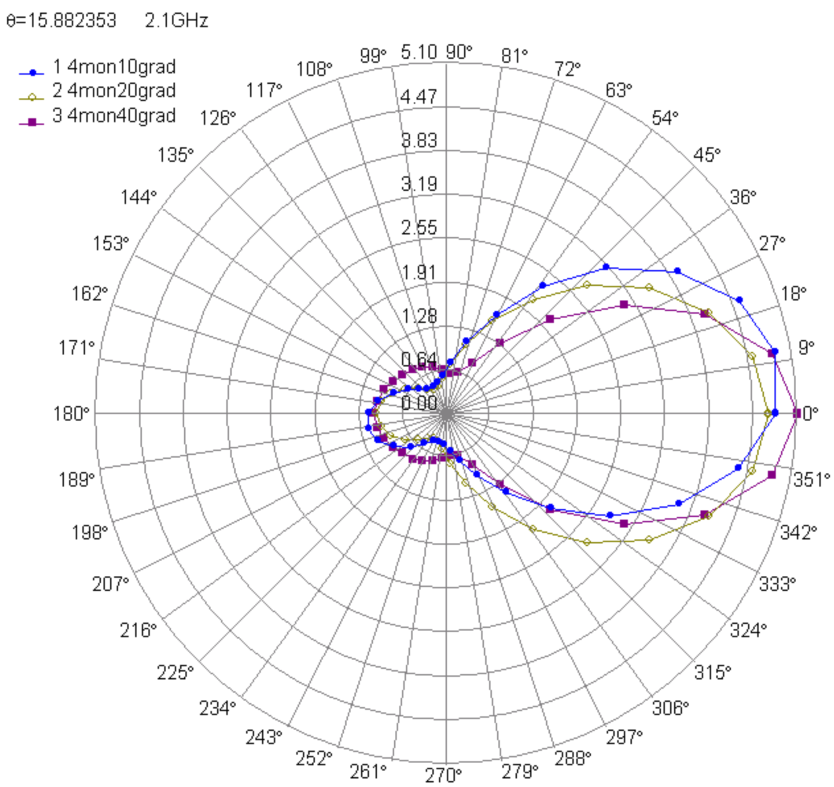


**Figure 15 Azimuth radiation pattern for the four monopoles case (linear scale)**

The graph for the 10 degrees case in Figure 15 can be observed to be slightly slanting to one side. This is due to a small design error and should be 10 degrees lower. In this case the higher the angel becomes between the four monopoles the narrower the radiation becomes. This is the same exact effect as for the previous cases. The increase in frequency also increases the elevation angle slightly. This yields for all cases in section 3.1 where the frequency is increased. Again it is assumed that this is because of the mismatch between the heights of the monopoles.

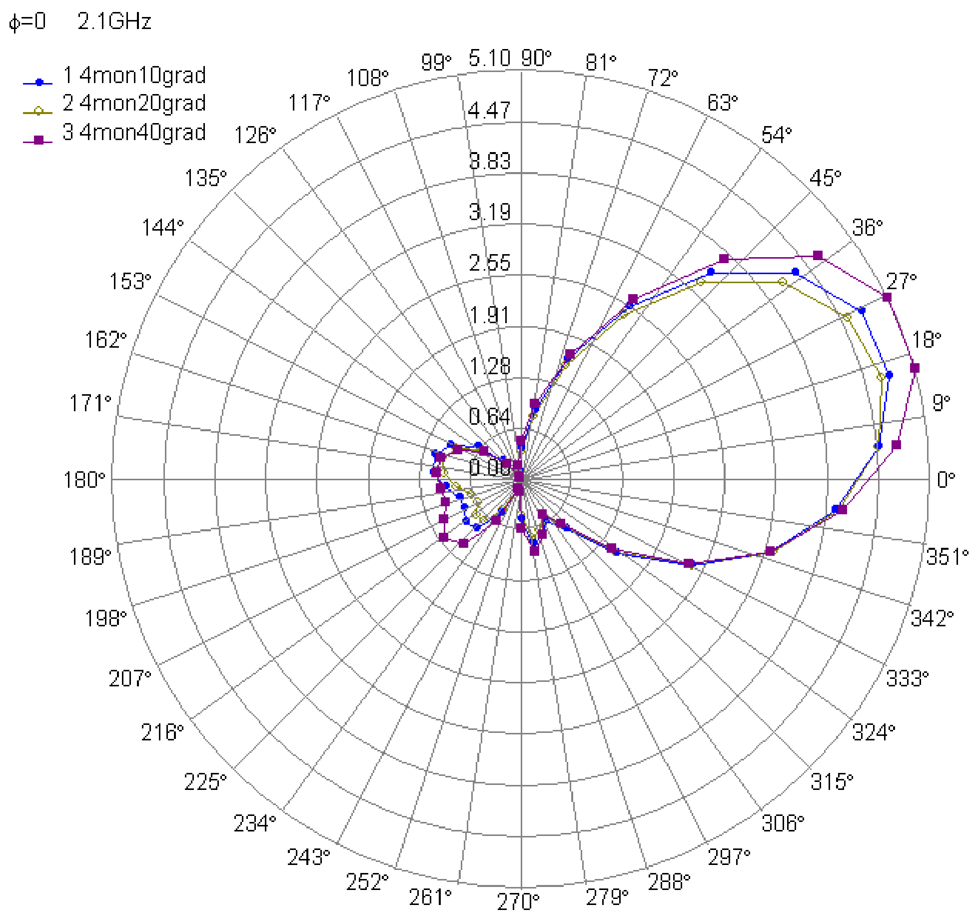


**Figure 16 Elevation radiation pattern for the four monopoles case (linear scale)**

### 3.1.6 Five parasitic monopoles

In this section the use of five connected parasitic monopoles will be discussed. It has the same configuration as the previous sections.

Again one can observe from Figure 17 much the same increase in the reflection factor for increasing angle as for the earlier cases. One can also observe from the previous sections that the more monopoles that are connected the worse the matching gets. In section 3.1.7 these effects will be summarized and discussed.

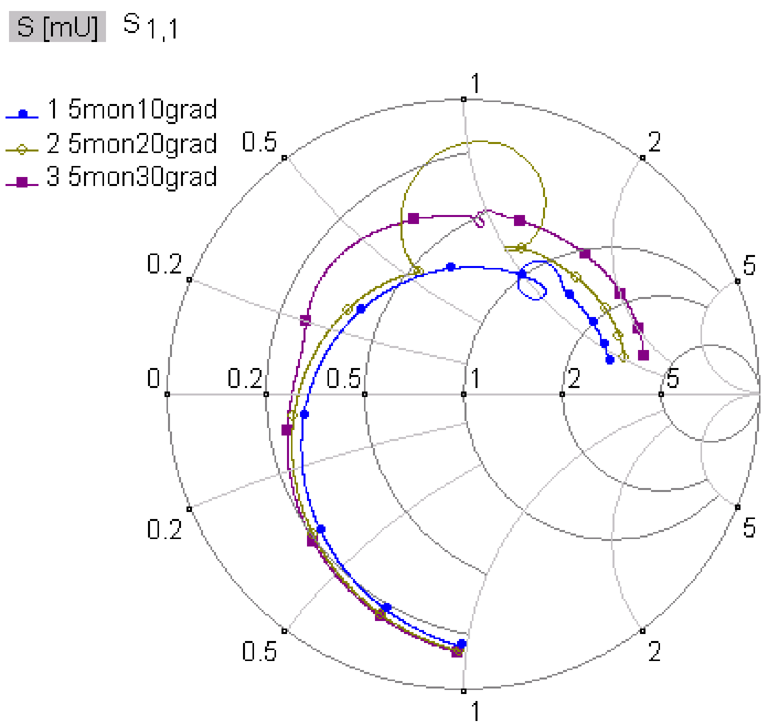


**Figure 17 Smith chart for five parasitic monopoles**

## Radiation patterns

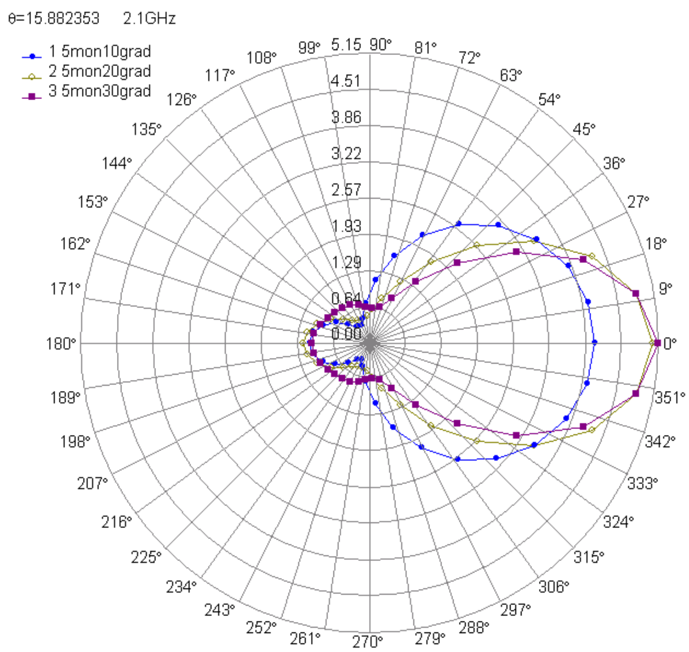


**Figure 18 Azimuth radiation pattern for five parasitic monopoles (linear scale)**

As for the earlier cases, the larger the angles between the monopoles are the narrower the beam-width. This is shown in Figure 18. The gain is slightly lower for the 10 degrees case than for the rest. The elevation radiation patterns are shown in Figure 19.

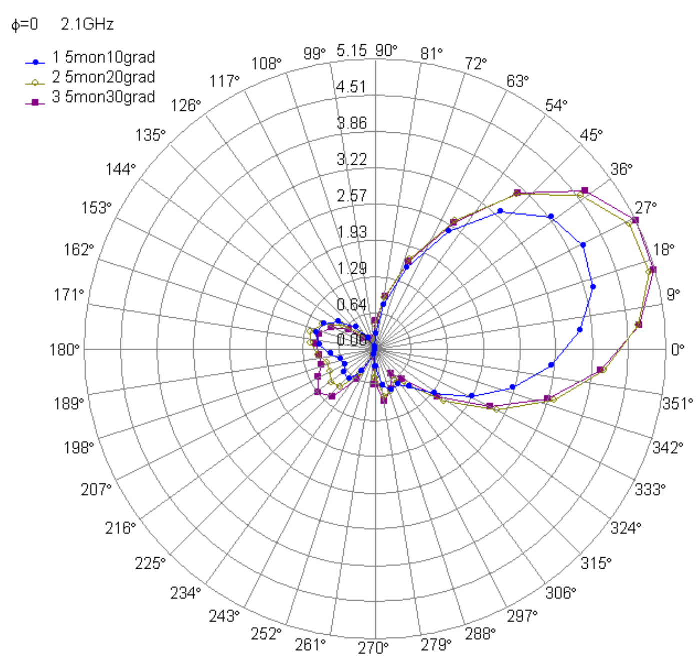


**Figure 19 Elevation radiation patterns for five parasitic monopoles (linear scale)**

### 3.1.7 Beam widths and elevation angles

| Frequency (GHz) | Number of monopoles | Angle between monopoles | Gain (dB) | Gain (linear) | Half power beam width (degrees) | Elevation angle | VSWR | Front to back ratio(dB) |
|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 20 | 5.9 | 3,86 | 140 | ~20 | 2,3 | 3.7 |
| 2 | 2 | 40 | 5.9 | 3,86 | 105 | ~20 | 2,6 | 2.7 |
| 2 | 2 | 60 | 5.9 | 3,86 | 100 | ~20 | 2,8 | 2.7 |
| 2 | 2 | 80 | 5.4 | 3,47 | 80 | ~20 | 3.3 | 0.3 |
| 2 | 2 | 100 | 5.0 | 3,15 | 80 | ~20 | 4.0 | -1.2 |
| 2 | 3 | 10 | 6.0 | 4,00 | 105 | ~20 | 2.4 | 4.3 |
| 2 | 3 | 30 | 4.8 | 3.00 | 150 | ~20 | 2.5 | 0.4 |
| 2 | 3 | 50 | 6.3 | 4.30 | 65 | ~20 | 3.8 | 4.3 |
| 2 | 3 | 70 | 3.2 | 2.10 | 100 | ~20 | 4.7 | -3 |
| 2.1 | 3 | 10 | 5.4 | 3.50 | 145 | ~25 | 2.5 | 4.1 |
| 2.1 | 3 | 30 | 6.4 | 4.40 | 95 | ~25 | 3.0 | 5.4 |
| 2.1 | 3 | 50 | 6.8 | 4.83 | 75 | ~25 | 3.8 | 5.2 |
| **2.1** | **3** | **60** | **6.8** | **4.81** | **70** | **~25** | **4.2** | **5.9** |
| 2.1 | 3 | 70 | 5.9 | 3.90 | 70 | ~25 | 5.3 | 4.8 |
| 2.1 | 4 | 10 | 6.8 | 4.80 | 95 | ~25 | 3.0 | 5.8 |
| 2.1 | 4 | 20 | 6.6 | 4.60 | 100 | ~25 | 3.3 | 5.6 |
| 2.1 | 4 | 30 | 7.1 | 5.10 | 70 | ~25 | 4.3 | 6.1 |
| 2.1 | 5 | 10 | 5.9 | 3.90 | 135 | ~25 | 2.7 | 4.6 |
| 2.1 | 5 | 20 | 7.1 | 5.10 | 85 | ~25 | 3.4 | 6.1 |
| 2.1 | 5 | 30 | 7.1 | 5.15 | 70 | ~25 | 4.4 | 6.2 |

**Table 1 Radiation characteristics for the different cases**

It can be observed from Table 1 that the more parasitic monopoles used the higher the gain becomes. This suggests that five monopoles is the best solution out of these cases. However there are other things to consider. The matching is the largest problem. Generally the matching gets worse the more monopoles that are placed on the ground plane. But it might be possible to mend this by introducing reactive elements on the connections of the parasitic monopoles, but this may also affect the radiation. Other matching schemes can also be used, that does not affect the radiation as described in section 4.3. The highlighted situation is the one that is seen upon as the most ideal for this case. This is a compromise between different factors which is often the case for working with antenna design. For this situation the beam width is the best but for the gain and matching other solutions will be better. Since the main application of this antenna depicts a relatively narrow beam width, this is seen upon as the most important factor. In the following section this configuration will be investigated further.

In chapter 4 simulations be more complex simulation tool will be performed and the matching scenario will be discussed.

### 3.2 Further exploration of one of the cases

From the data presented in Table 1, it is decided to explore further the situation with three parasitic monopoles with an angular distance of 60 degrees between each monopole. This situation is highlighted in bold letters in Table 1. In this section the impact the height and radius of the monopoles has on the antennas characteristics will be investigated. It will also be discussed how the length of the skirt and the size of the ground plane affect the properties of the antenna.

#### 3.2.1 Varying the radius of the monopoles

The radiuses of the monopoles have an effect on both the radiation and the matching of the antenna. Therefore it is important to examine the effects that this parameter has on these properties. A wider monopole will also have a positive effect on the bandwidth of the antenna.[4]

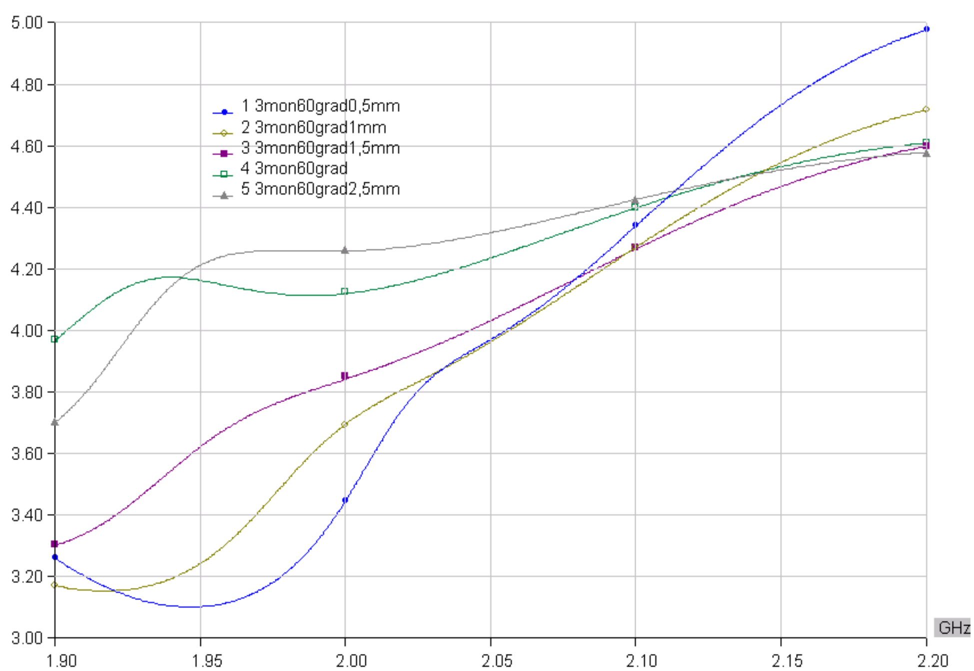


**Figure 20 VSWR for different radiuses for the monopoles**

The monopoles will not be varied individually. The radius of all the monopoles will be varied together and by the same parameter. This is done for simplicity. Again the legends in the following figures are descriptive for which case the graph represents. For instance the legend “3mon60grad0,5mm” depicts that this is the three monopoles case, with 60 degrees angle between the parasitic monopoles. The last part shows the monopoles radiuses. In Figure 20 the VSWR for the different radiuses at shown. The fourth graph lacks the radius in the legend. This is the original case, with a radius of 2 mm.

One can observe that the matching generally gets worse the thicker the monopoles get. But this is not by a great deal for 2.1GHz which in section 3.1.4 was chosen as the best frequency at this stage of the design. It is clear that the thickness of the monopoles does not affect the matching of the antenna by any great factor. But it seams that the thicker the monopole gets the more level the VSWR becomes. This can indicate that a thicker monopole will increase the bandwidth. This is a logical assumption since this is a general theoretical effect for simple antennas as monopoles and dipoles. [4]

## Radiation patterns

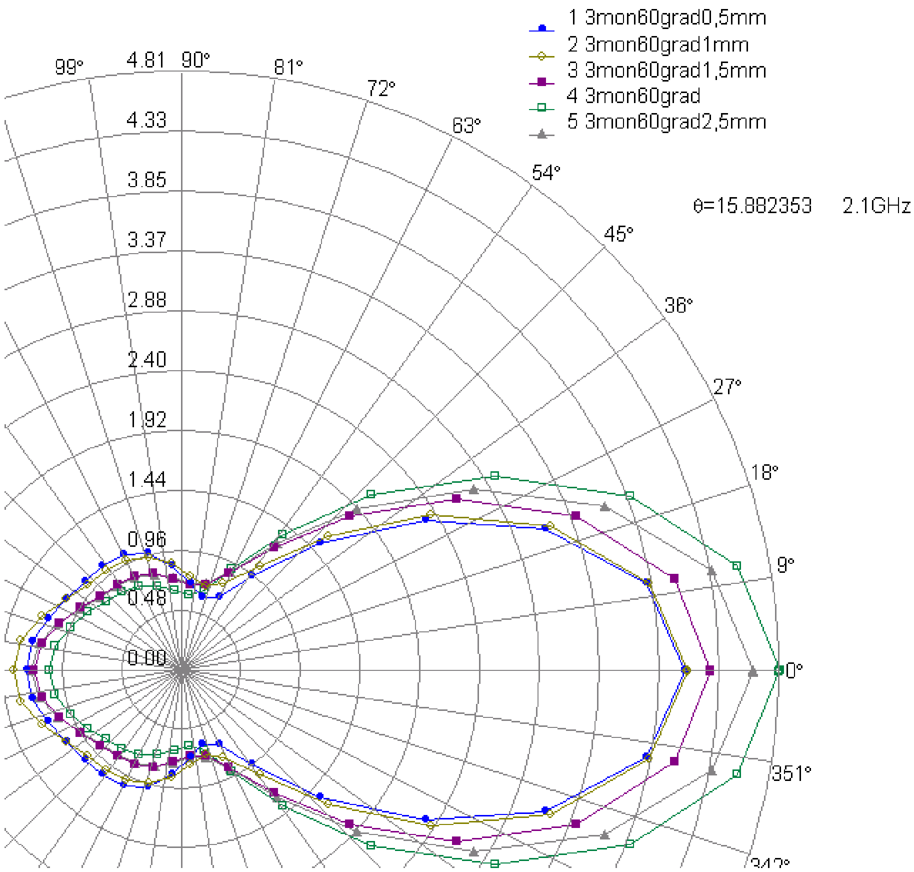


**Figure 21 Azimuth radiation patterns (linear scale)**

From Figure 21 one can extract that the gain as well as the front to back ratio is best for a radius of 2mm, which was the original radius used in the previous sections. There is no difference in the elevation angle of the radiation, thus this will not be illustrated. These results show that it is logical to choose a radius of 2 mm to be used in the further exploration of the antenna.

### 3.2.2 Height of the monopoles

In the previous cases the height of the active monopole is 35 mm, and 33 mm for the passive monopoles. The active monopole was best matched when alone at a height of 35 mm. See section 3.1.1 for details. This was discovered early in the process of exploring this antenna. Therefore this section will concentrate on the height of the passive monopoles alone, with a fixed height of the active monopole at 35 mm.

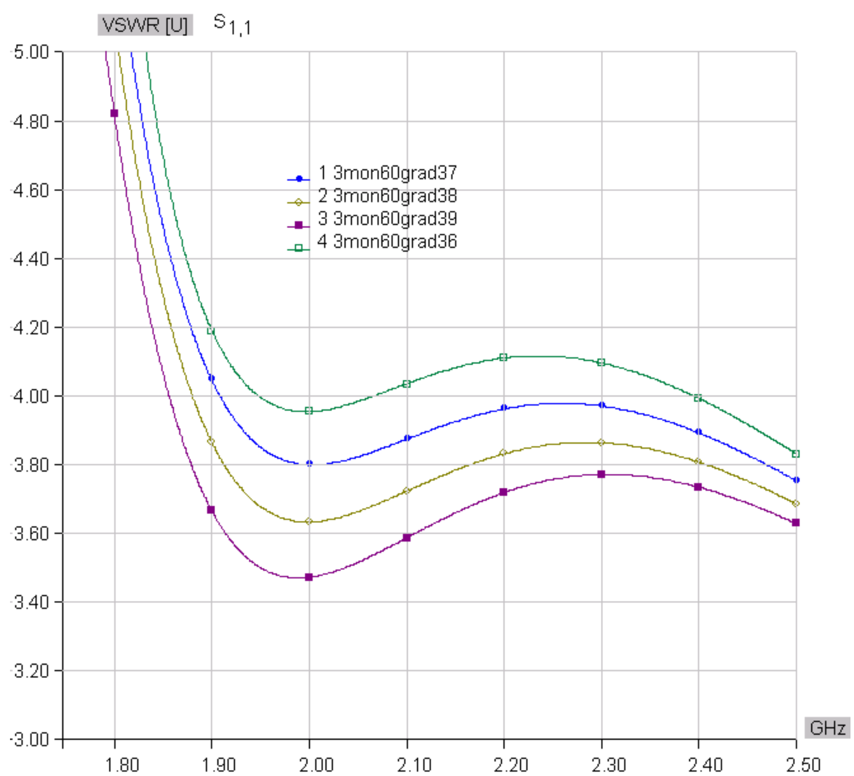


**Figure 22 VSWR of the varying heights of the monopoles (the last number in the legends are the parasitic monopole heights)**

It can be observed from Figure 22 that the higher the monopole the better the matching becomes. This is valid up to a certain point, which is illustrated in Table 2. The Smith chart for these cases show very small differences between the cases; therefore this will not be presented.

## Radiation patterns

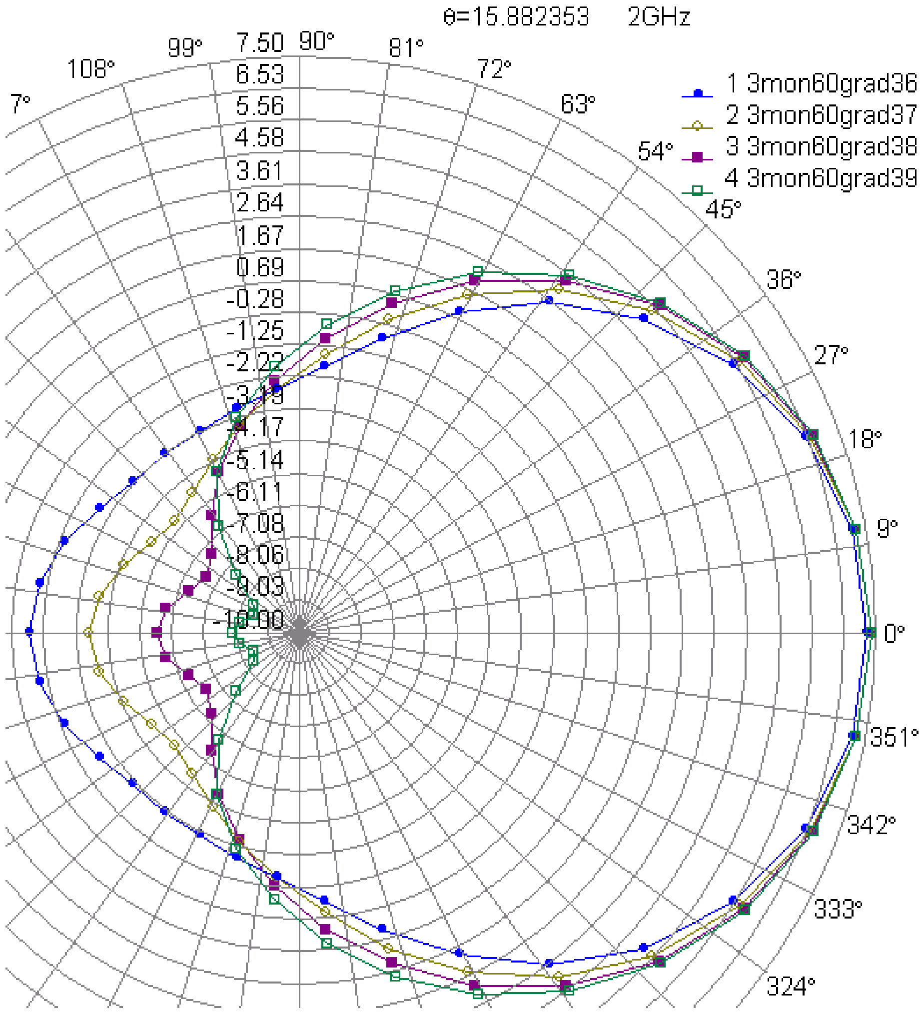


**Figure 23 Azimuth radiation pattern (dB scale)**

As can be seen in Figure 23 the higher the monopole is the lesser backward radiation occurs. The gain is virtually the same for all the cases. One other observation that can be made is that the higher the monopoles are the wider the half power beam width becomes. See Table 2 for a summary of all the cases in this section. The elevation angles are the same for all the cases and the elevation radiation patterns are so similar too the previous cases that the will not be considered for this case. The frequency is now set to 2.0 GHz since it now was possible to tune the antenna very accurately.

### 3.2.3 Summary of monopole variations

| Frequency (GHz) | Height (mm) | Radius (mm) | Gain (dB) | Half power beam width (degrees) | Elevation angle | VSWR | Front to back ratio(dB) |
|---|---|---|---|---|---|---|---|
| 2.1 | 33 | 0.5 | 6.1 | 80 | ~20 | 4.3 | 5.1 |
| 2.1 | 33 | 1.0 | 6.1 | 80 | ~20 | 4.25 | 5.0 |
| 2.1 | 33 | 1.5 | 6.3 | 90 | ~20 | 4.25 | 5.5 |
| 2.1 | 33 | 2.0 | 6.8 | 80 | ~20 | 4.35 | 6.8 |
| 2.1 | 33 | 2.5 | 6.1 | 80 | ~20 | 4.4 | 5.3 |
| 2 | 36 | 2.0 | 7.4 | 75 | ~20 | 3.95 | 9.1 |
| 2 | 37 | 2.0 | 7.4 | 85 | ~20 | 3.8 | 11 |
| 2 | 38 | 2.0 | 7.4 | 90 | ~20 | 3.65 | 12.9 |
| **2** | **39** | **2.0** | **7.4** | **90** | **~20** | **3.45** | **16** |
| 2 | 40 | 2.0 | 7.4 | 95 | ~20 | 3.35 | 17.5 |
| 2 | 41 | 2.0 | 7.3 | 100 | ~20 | 3.20 | 20.8 |
| 2 | 42 | 2.0 | 7.3 | 103 | ~20 | 3.05 | 22.3 |

**Table 2 Summary of the different cases**

Table 2 shows that the higher the parasitic monopoles are, the better the matching becomes. The front to back ratio also increases with increasing height. The downside of this increase in height is the raise in half power beam width. In further investigations the case highlighted in bold letters are used because it represents a compromise between the matching and the beam width, where the beam width is considered the most important parameter.

### 3.2.4 Height of skirt

As mentioned in section 2 the skirt that is added is for the purpose to lower the angle of radiation of the antenna. In this section the effect of varying the height of this skirt will be explored.

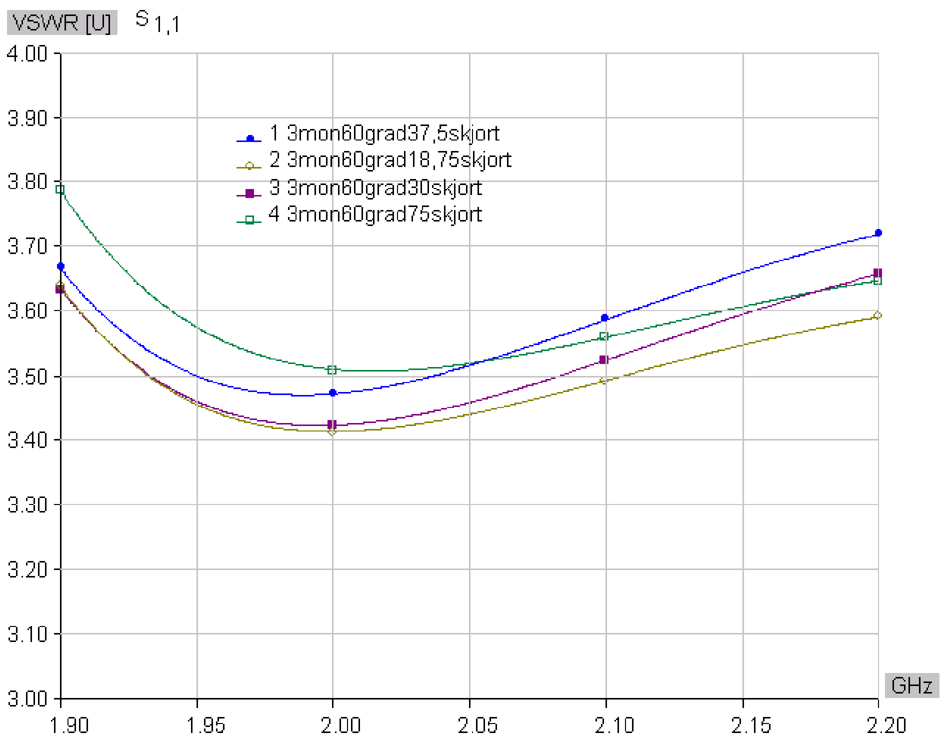


**Figure 24 VSWR for different lengths of skirt**

Figure 24 depicts that the length of the skirt is not a very important factor for the matching of the antenna. But for the gain and elevation angle of the antennas maximum radiation, it has more apparent effect.

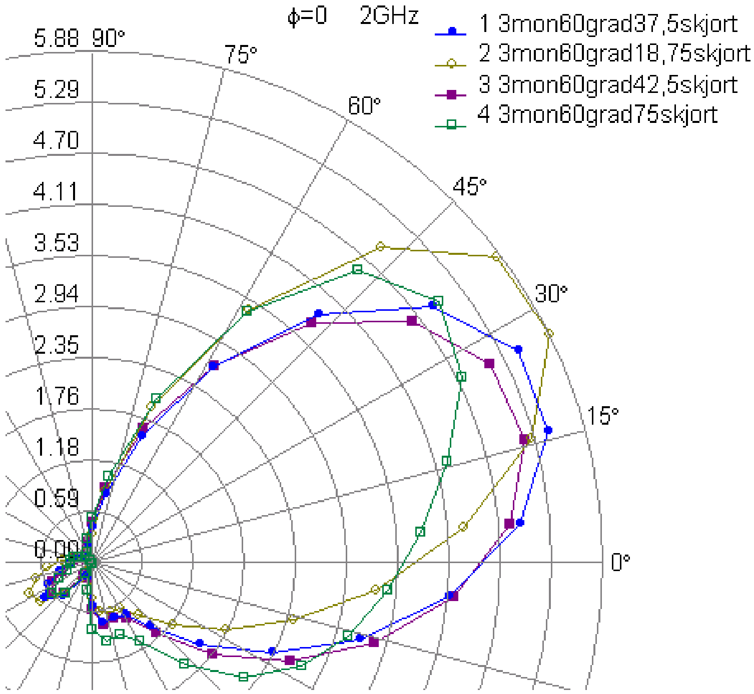


**Figure 25 Elevation radiation pattern for different lengths of skirt (linear scale)**

As can be seen from Figure 25, the best gain and the lowest elevation angle occurs for the original skirt length of 37.5 mm, or equivalent to a quarter wavelengths. This shows that the skirt length found in the literature is the optimal length for this antenna. But the figure also shows that the length of the skirt is not very important factor of the design regarding the gain, but it have to be present to lower the angle of maximum radiation. [1]

### 3.2.5 Size of the ground plane

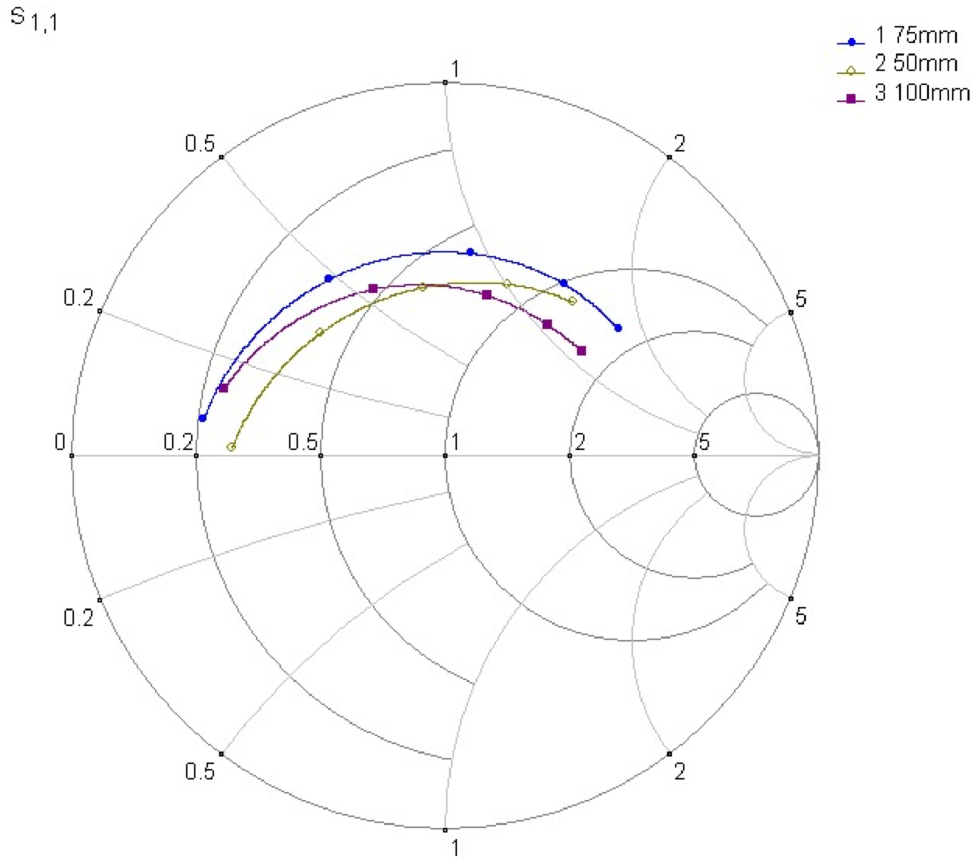


**Figure 26 Smith chart for the different sizes of ground plane**

As can be seen from Figure 26 the matching is not very much affected by the size of the ground plane. But the Smith-chart shows that the matching is actually worst for the original case with a radius of 75 mm. But this is not by such a large factor that it is taken in to serious consideration since they are all quite badly matched.

Figure 27 shows that there is a larger difference in the radiation of the antenna than in the matching. The larger the ground plane becomes the higher the elevation of the radiation gets. But the gain of the antenna increases slightly with increasing size of the ground plane. The half power beam width does not change substantially, but is generally a bit better for the case with a 50 or 75 mm radius ground plan than for the case with a radius of 100 mm. Since the size of the antenna also is an important factor, and the change in elevation angel is more substantial then the decrees in gain, the radius of the antenna is kept at 75 mm as a compromise between gain and elevation angel.

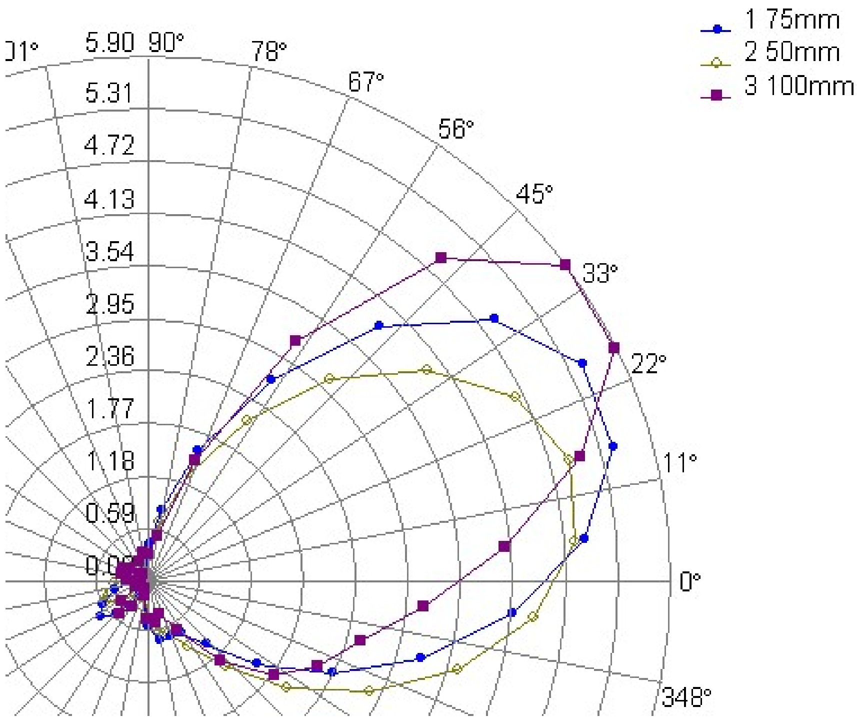


**Figure 27 Elevation radiation pattern according to the radius of the ground plane (linear scale)**

## 3.3 Quarter-wave ground plane model

In this section a model which has a ground plane with a radius of 0.25λ and a skirt with a height of 0.25λ will be discussed. The monopoles used for excitation are 35 mm in height and the reflectors are 39 mm. The reflectors that are thought to be switched in as active monopoles are also 35 mm. As an example the middle of the three reflectors in Figure 28 is 35 mm.

### 3.3.1 Description of the different cases

In this section it will be given a short description of how the different configurations are constructed.

**Two reflectors**

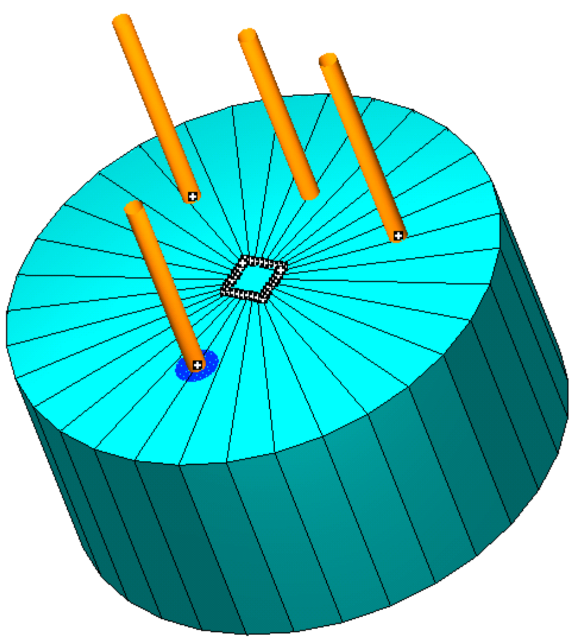

**Figure 28 Two reflectors, single active monopole**

This case is designed to switch the active state between two different monopoles. The two monopoles that are to be used as active are the single monopole at the bottom of Figure 1, and the center monopole of the group of three in the same figure. The two reflectors are placed 60 degrees apart, when referred to the bottom active monopole. The dimensions of the antenna are as described in the start of this section. This case is denoted “2mon” in the legends in the following figures. This antenna will have a narrower beam width in the direction from the reflectors to the active monopole than in the opposite direction.

### Three reflectors

This is the same case shown Figure 28, with one difference. All three monopoles in the top group in Figure 28 are used as reflectors. The switching of active monopole will be done the same way as described for the cases in section 3.1 and 3.2 . This case is denoted “3mon30deg” in the legends in the following figures.

### Three reflectors 60 degrees

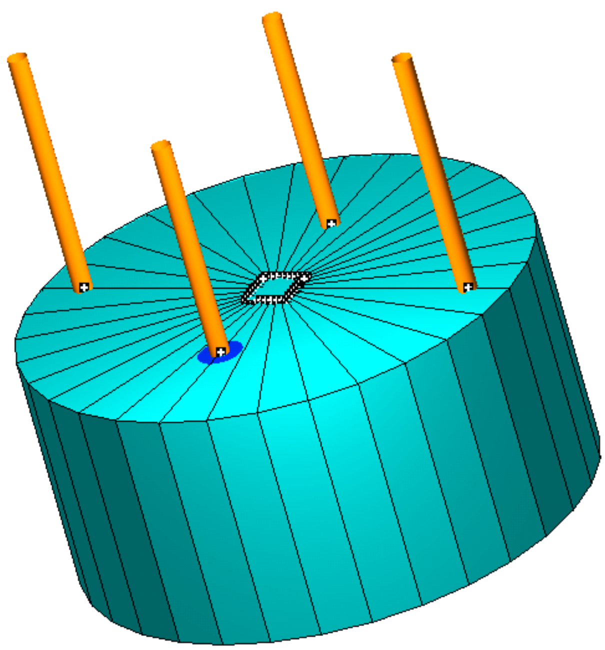

**Figure 29 Illustration of the case with three reflectors with 60 degrees spacing**

This is nearly the same case as the previous two cases. The angle between the reflectors is now set to 60 degrees. The switching is still the same. This case is denoted

“3mon60deg” in the legends in the following figures. The configuration is shown in Figure 29.

### Edge monopoles

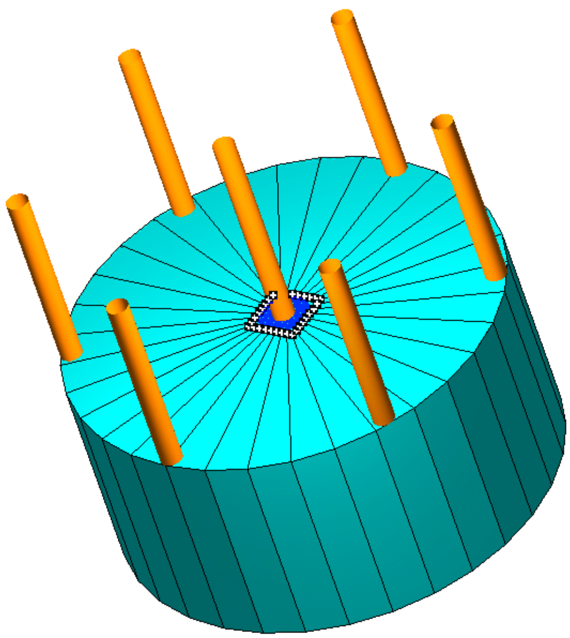

**Figure 30 Illustration of edge monopoles case**

In this case six monopoles are placed around the outer rim of the ground plane as shown in Figure 30. The ground plane is extended to 39.5 mm from the 37.5 mm original ground plane. This is done so that the whole of the monopoles stands on the ground plane. Three and three monopoles are used as reflectors and the active monopole is always placed in the middle. This case is the same as the ones discussed in sections 3.1 and 3.2 but with a much smaller ground plane. This case is denoted “kandtkvart” in the legends in the following figures.

### 3.3.2 Simulations

In this section simulations on the configurations described in section 3.3.1 will be performed.

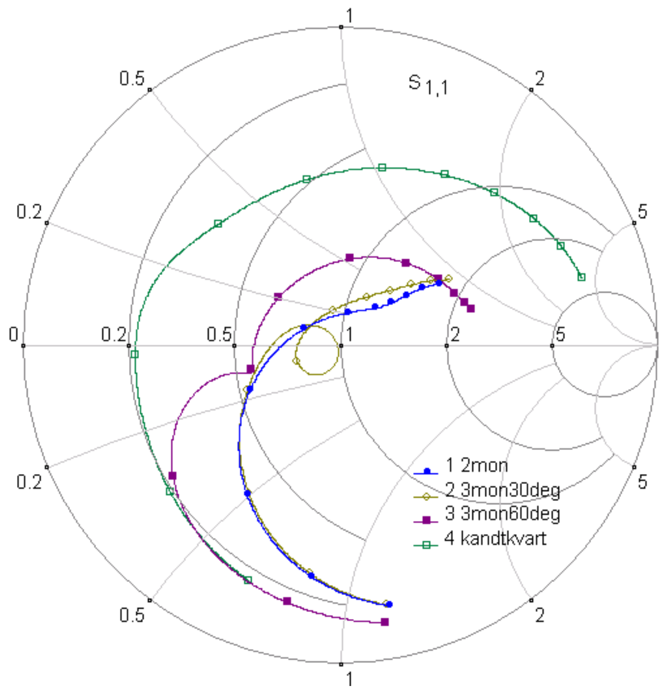


**Figure 31 Smith chart for the different cases**

From Figure 31 it can be extracted that the case with the edge monopoles has much worse matching than the other three cases. This can indicate that it is having a center active monopole that leads to the bad matching. But it must be taken in to consideration that this is the case with the most monopoles and this was earlier discovered to be one of the causes for bad matching.

## Radiation patterns

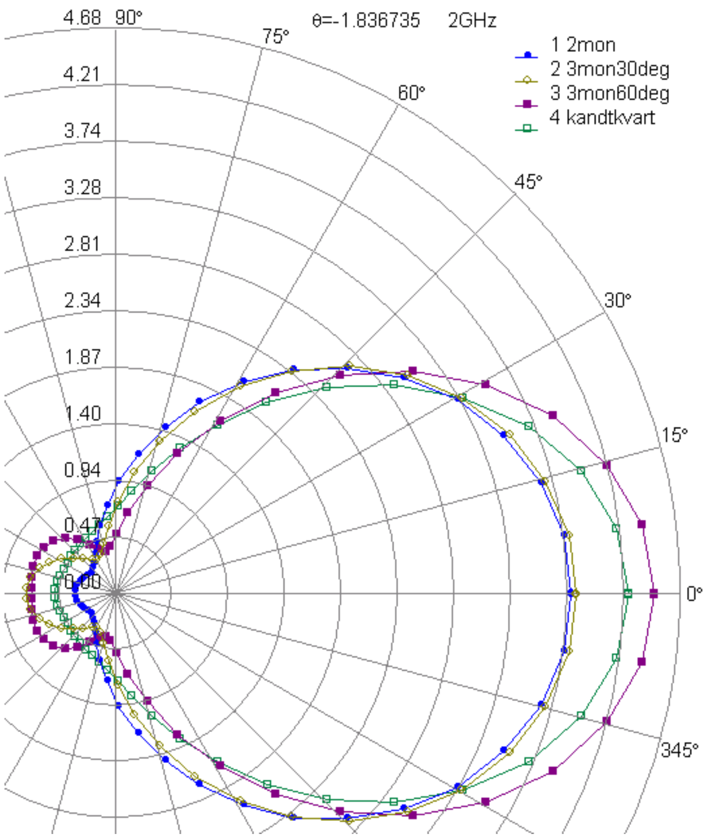


**Figure 32 Azimuth radiation patterns (linear scale)**

Figure 32 shows that there is not much variation in gain between the different cases. The half power beam width is a bit narrower for the cases with three connected monopoles. In Figure 33 however larger and more important differences can be observed. The elevation angles of all of the antennas are much lower than for the cases discussed in sections 3.1 and 3.2. For the three first cases in Figure 33 the elevation angle is as low as about 5 degrees. This is very preferable since radiation is wished to have a maximum in the vertical direction (see chapter 1). See Table 3 for summary of the parameters for the cases discussed in this section.

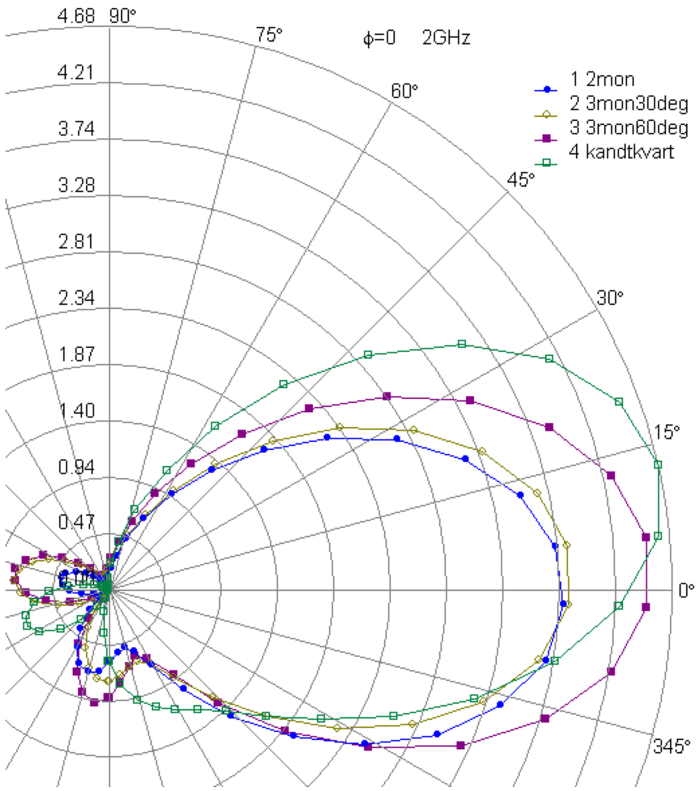


**Figure 33 Elevation radiation patterns (linear scale)**

| Frequency (GHz) | Case | Gain (dB) | Half power beam width (degrees) | Elevation angle (degrees) | VSWR | Front to back ratio(dB) |
|---|---|---|---|---|---|---|
| 2 | 2mon | 5.6 | 120 | ~5 | 1.3 | 11.6 |
| 2 | 3mon30deg | 5.6 | 120 | ~5 | 1.3 | 7.1 |
| 2 | 3mon60deg | 6.4 | 100 | ~5 | 1.8 | 7.9 |
| 2 | Kandtkvart | 6.2 | 110 | ~15 | 3.8 | 9.2 |

**Table 3 summary**

As can be seen from Table 3 summary, the best case is probably the “3mon60deg”, since this is the case that both have the required VSWR and the narrowest beam width. The last case might be useful with a suitable matching scheme.

# 4 Simulations in EMDS

In this section some of the results from the simulations with WIPL-D will be compared with simulations done with the more complex EMDS software. [6] In addition simulations on a matching scheme will be performed.

## 4.1 Without matching

First a simple single monopole situation will be explored. This is the situation with only one active monopole in the center of the ground plane and no parasitic monopoles.

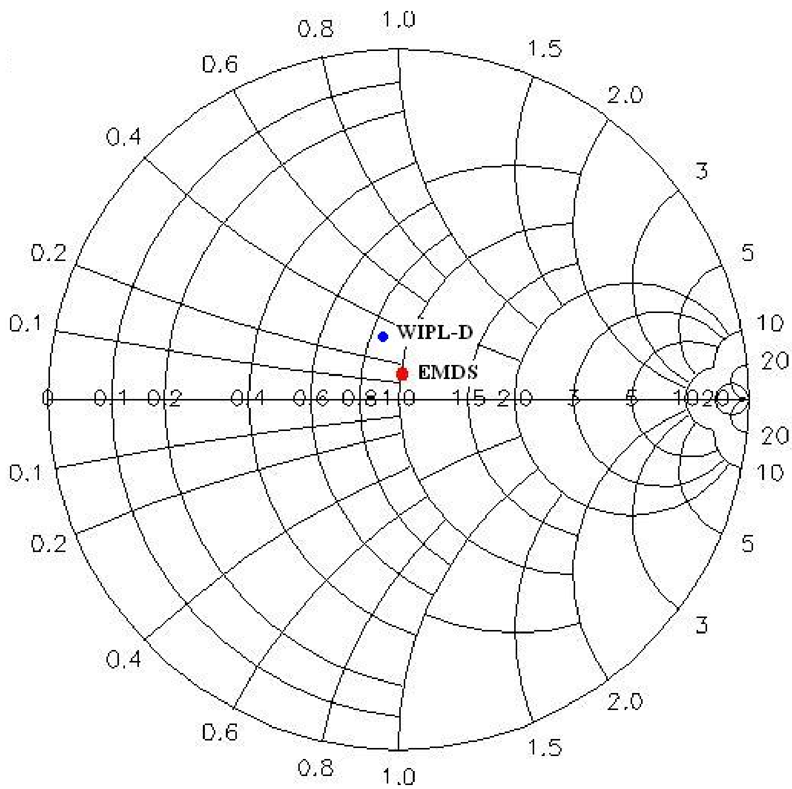


**Figure 34 Smith chart for the single active monopoles case**

Figure 34 shows that the two programs do not differ too much regarding the matching of the single active monopole. But this is a quite simple structure that does not require very much complex calculations, so the difference could be said to be quite significant when considering this.

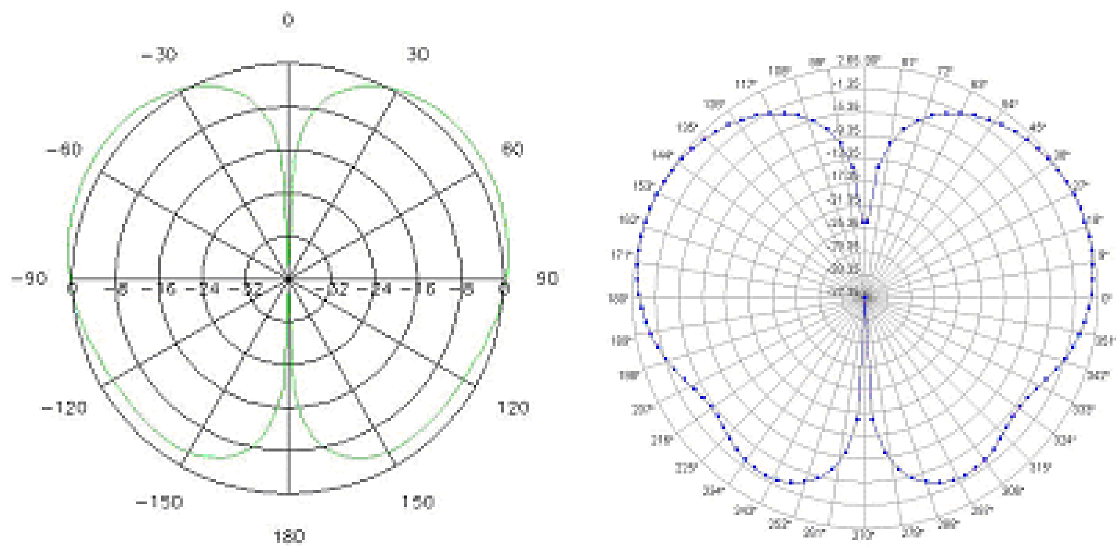

**Figure 35 EMDS (left) and WIPL-D elevation radiation patterns**

As can be observed in Figure 35 WIPL-D and EMDS calculates quite similar results regarding the radiation. Because of the higher complexity in the calculations used in EMDS it is logical to conclude that it is the results from this program that are the most accurate, even tough the result in this case is quit similar. The reason for not using EMDS for all the simulations is that this program uses a very long time for each simulation. Almost 300 times as long as simulations made in WIPL-D.

## 4.2 Three parasitic monopoles

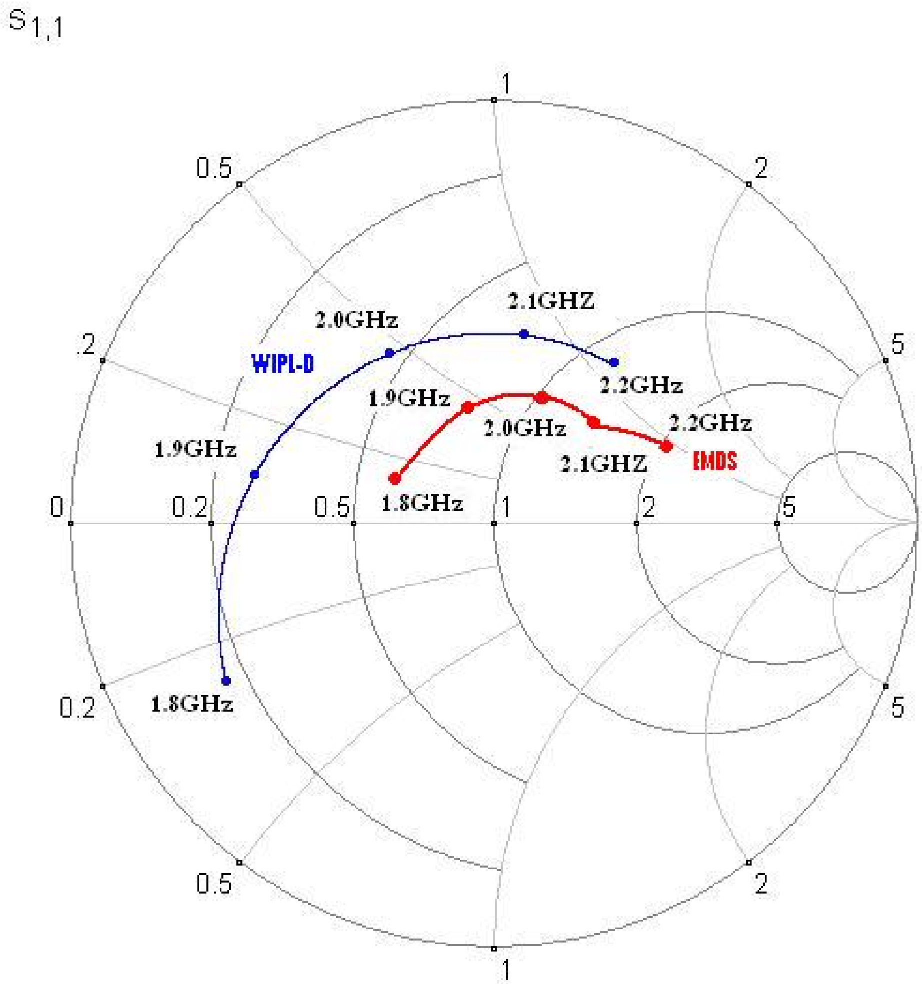


**Figure 36 Smith chart for three parasitic monopoles**

In Figure 36 one can observe large differences in the simulated matching of the antenna. It is difficult to conclude why this is. It could be made a mistake in the modeling, or one of the programs can be severely wrong in its calculations. The matching calculated in EMDS is much better than the one calculated with WIPL-D.

The model used in EMDS is the same as in the previous section only added the three parasitic monopoles. Based on the similarity in Figure 34 it can be assumed that there is quite a big difference in the results displayed by the two programs, and not a mistake in the modeling.

**Radiation patterns**

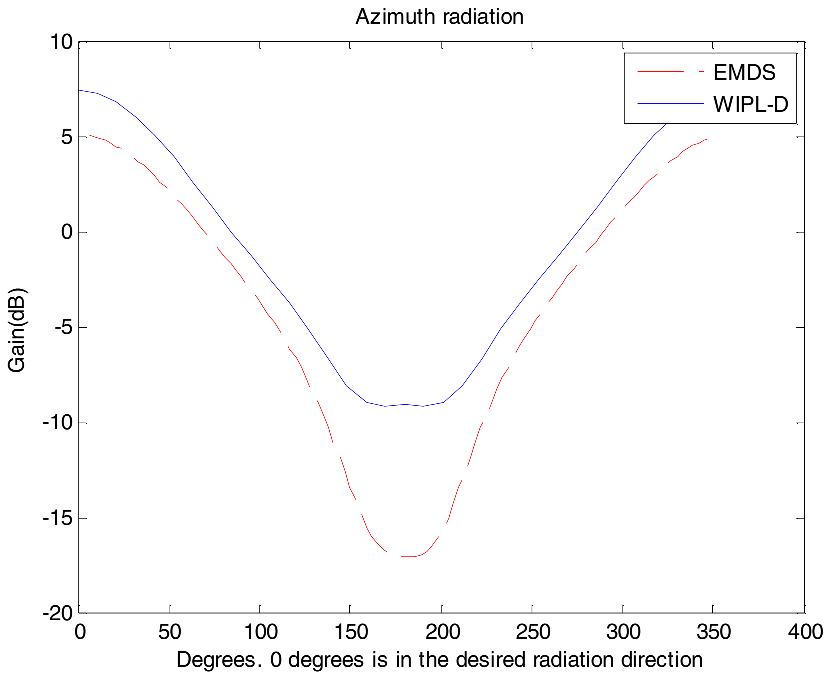


**Figure 37 Azimuth radiation**

From Figure 37 it can be observed that WIPL-D returns a result that has a 2 dB higher gain, but larger backwards radiation. The cut in this figure is taken at an elevation angel of about 25 degrees, which is the simulated angel of maximum gain for this configuration. There is quite a large difference between the results. There is a slight difference in the presentation of data from the two programs. It seams that EMDS calculates the loss because of mismatch in to the gain calculations. This can be the reason for the difference in gain. But the difference in gain is much larger for the backward radiation than for the forward radiation. So it can be concluded that also in these characteristics the two programs show quite different results.

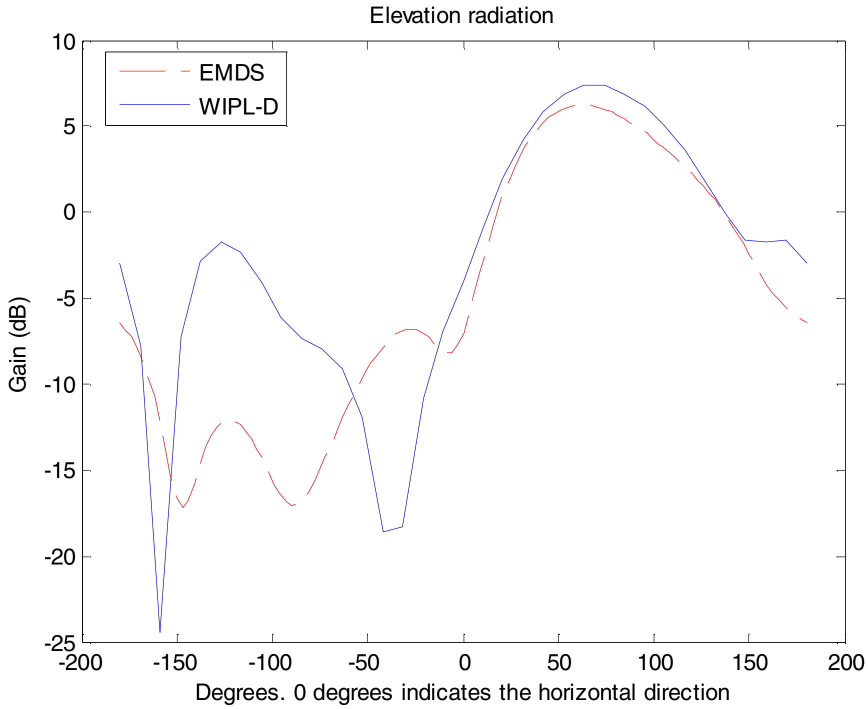


**Figure 38 Elevation radiation**

The difference between the two programs calculations of radiation characteristics becomes much clearer when reviewing Figure 38. The maximum gain is obtained for about the same elevation angle, but for the backwards radiation, large differences can be observed. It is difficult to conclude which program that is the most accurate one before any testing is performed. The results from the testing will be presented in chapter 5.

## 4.3 Matching

There are several possible matching schemes that can be used for this antenna. In this section only one will be discussed in detail. This is the use of a quarter wave transformer. This matching scheme leads to a low loss in power and is a quite easy way to match the antenna to a 50 ohm coaxial cable. The Smith chart in Figure 36 is used as basis for the matching. First the length of the 50 Ohm line originating at the bottom of the monopole will be calculated. This is the top narrow green outer coating of the blue center leader in Figure 39. This is done by rotating the 2.0 GHz point in the Smith chart in Figure 36 to the point where it intersects with the real impedance line in the Smith chart. [4] In this case this is 0.07 wavelengths or 12 mm, therefore the length of this first 50 Ohm line is to be 12 mm long.

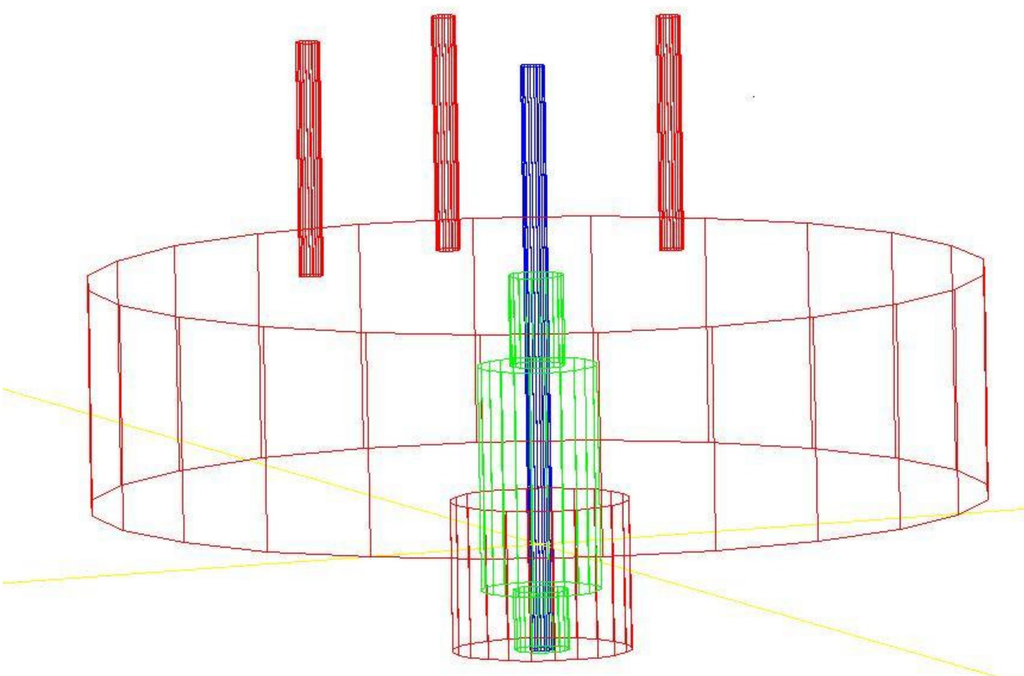

**Figure 39 the model used for matching simulations**

Since the real part of the impedance of the antenna now is about 100 Ohms the impedance of the quarter wave transformer should be abut 70 Ohms. [4]. This corresponds to an outer diameter of 6.3 mm when the inner diameter is 2 mm [7]. In this section the radiation patterns will not be discussed or shown. This is because there should be no difference in these depending of this type of matching scheme. And the measurements are going to be made without any type of matching scheme.

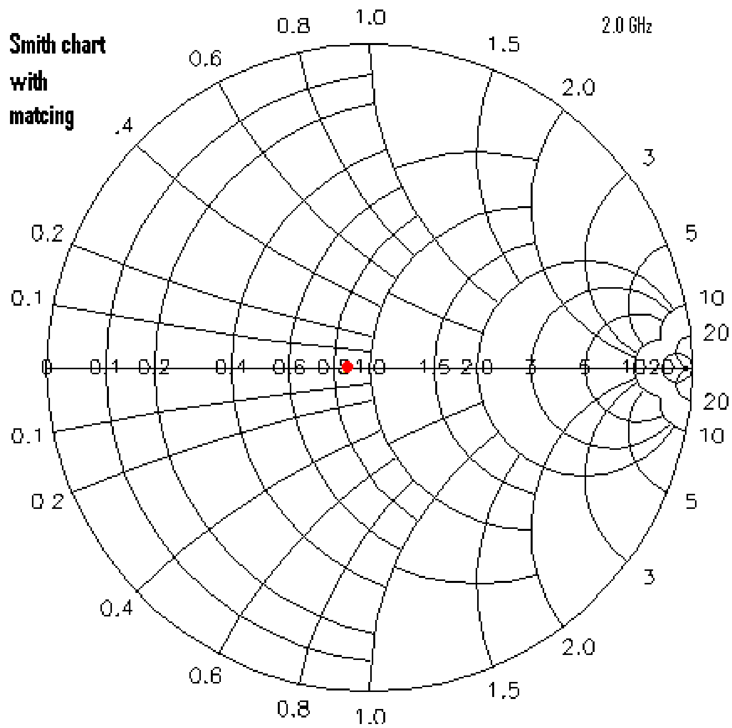


**Figure 40 Smith chart with matching**

As can be seen in Figure 40 the matching is now close to perfect. This corresponds to a return loss ratio of about 22 dB or a VSWR of 1.17 which is far below the requirements.

### 4.3.1 Removing the parasitic monopoles

The antenna is supposed to have satisfactory matching also without the parasitic monopoles, creating an omni directional antenna. Because of this it is necessary to simulate how the matching characteristics change when the parasitic monopoles are removed. As seen from Figure 41 the matching is far from perfect.

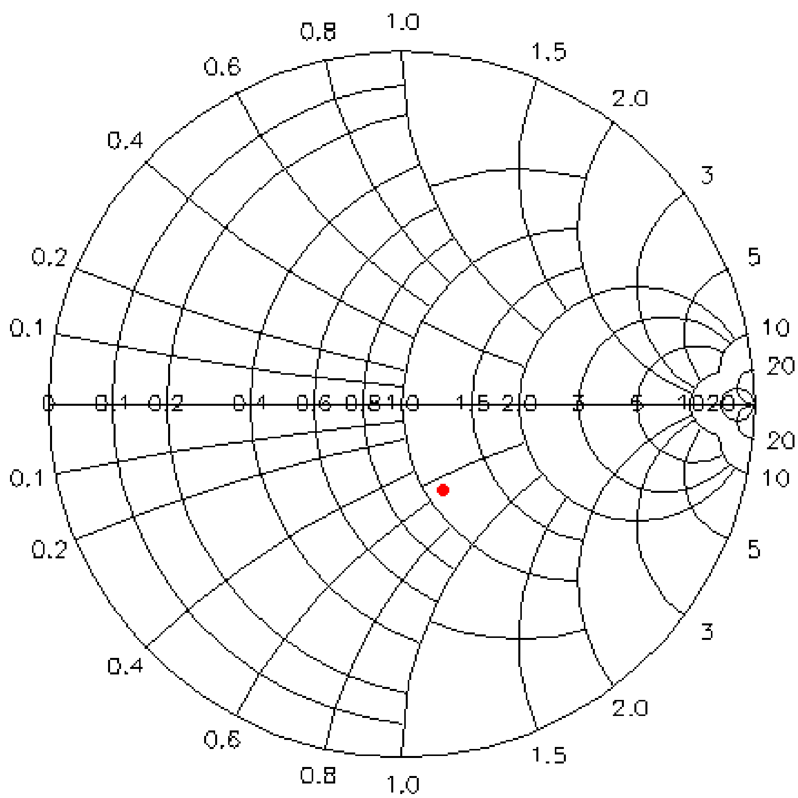


**Figure 41 Smith chart after removing the parasitic monopoles**

Because of this a different solution is chosen. By mismatching the antenna with the parasitic monopoles connected, we can get satisfactory matching for both cases.
The diameter of the outer conductor is set to 5.5mm by trial and error. This results in a characteristic impedance of about 60 Ohms [7]. The results are shown as a Smith-chart in Figure 42.

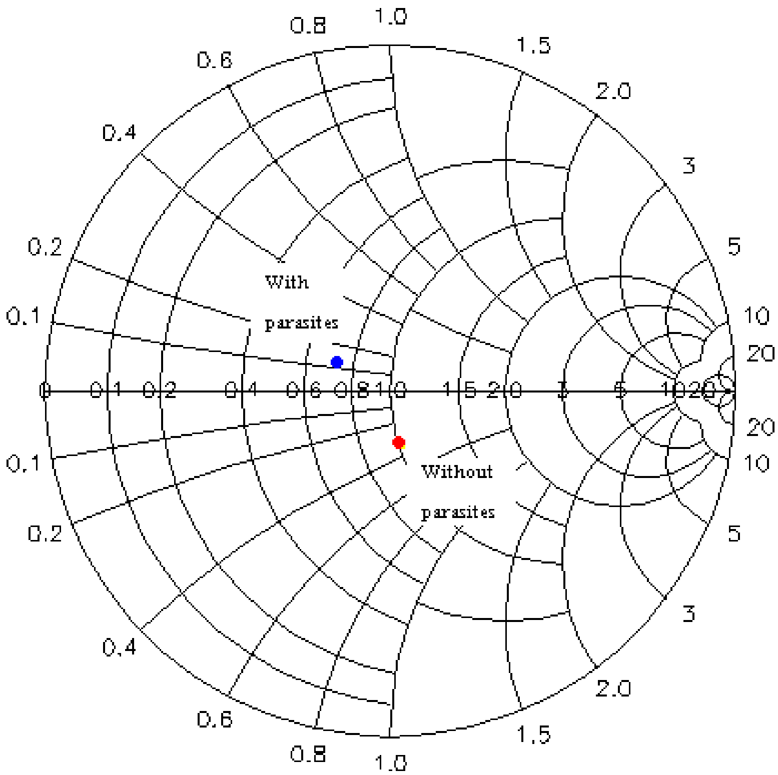


**Figure 42 Smith-chart after adjustment of impedance**

As can be seen from Figure 42 the matching is now satisfactory both with and without the connected parasitic monopoles.

## 4.4 Varying the length of the active monopole

The large difference between the two software's results indicates that further simulations needs to be made. In this section the length of the active monopole is varied in three steps between 33 and 37 mm with the three connected parasitic monopoles present but without any matching schemes.

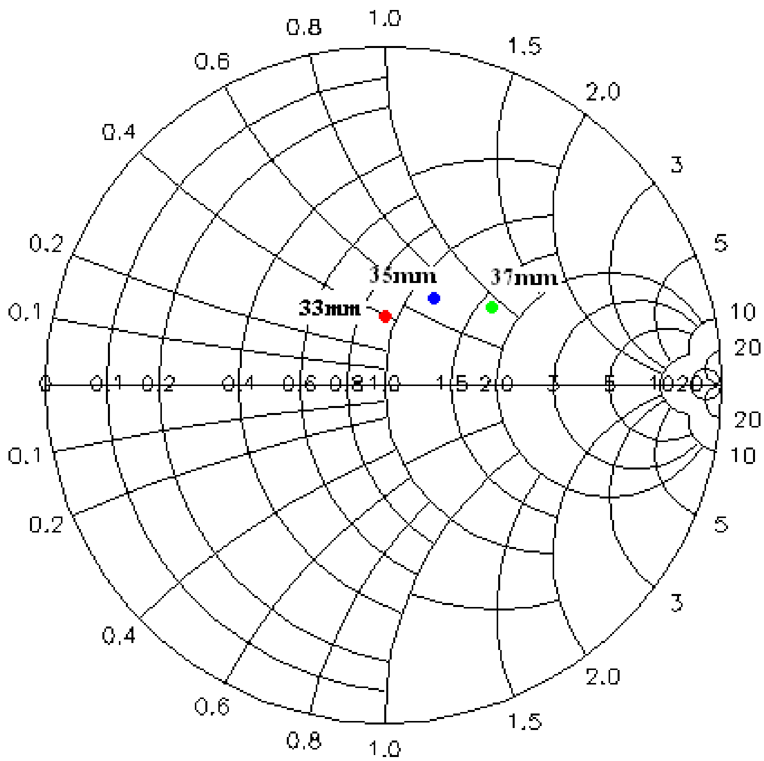


**Figure 43 Matching for the different lengths of monopoles**

As can be seen from Figure 43 the shorter the monopole gets the better the matching becomes. But as have been discussed in 3.2.2 the radiation characteristics are the best for the length of 35 mm. But testing will be performed for all three cases in section 5.

## 4.5 Bandwidth

In this section the bandwidth of the antenna characterized by the Smith chart in Figure 42, with the three parasitic monopoles connected will be simulated. The bandwidth of the antenna is defined as the percentages of the frequencies that lie bellow a VSWR of 2 in relation to the center frequency. A VSWR of 2 is about the same as a return loss of – 10 dB.

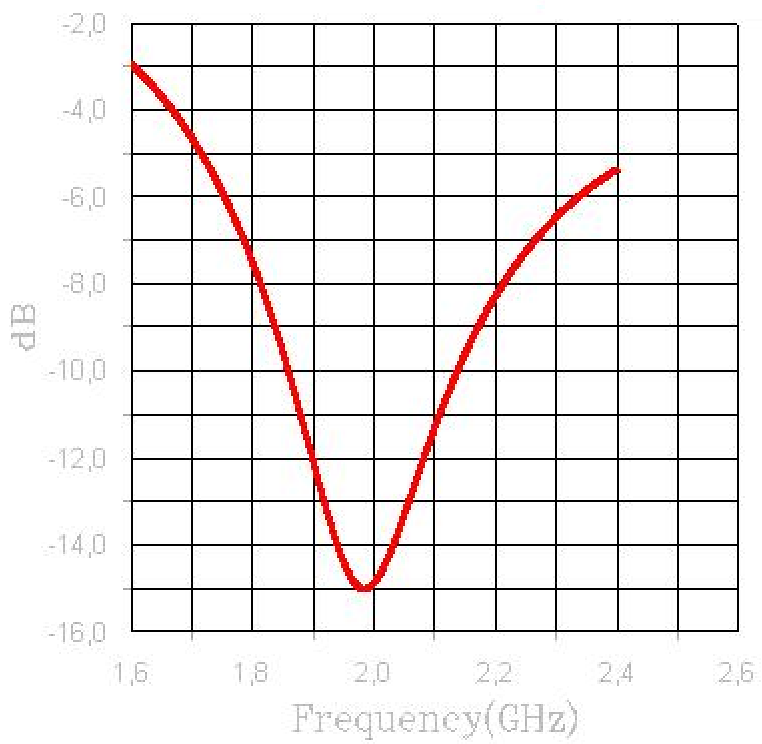


**Figure 44 Matching according to frequency with the connected parasitic monopoles**

As can be seen from Figure 44, the bandwidth of this antenna goes from about 1.85 GHz to about 2.15 GHz. This gives a bandwidth of 15 percent, which is above the desired bandwidth, of 10 %, discussed in chapter 1.

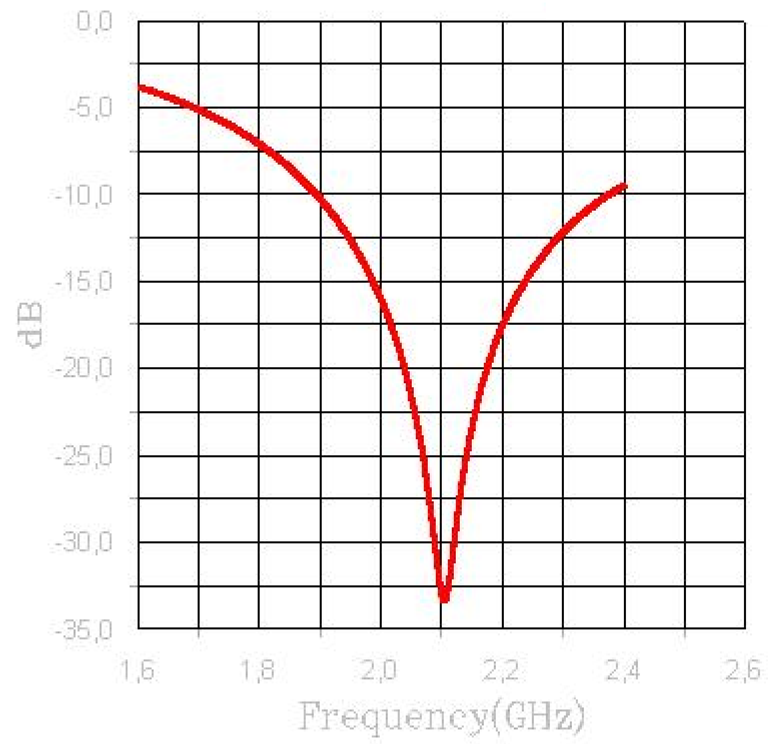


**Figure 45 Matching Bandwidth without the parasitic monopoles**

For the case with no connected monopoles the bandwidth follows the characteristics shown in Figure 45. It can be observed that the best matching is for this case displaced by about 100MHz. The bandwidth is now from about 1.9 GHz to about 2.35 GHz which is about 20% but with a center frequency of about 2.125 GHz. This is not ideal but still within the desired specifications.

Figure 44 and Figure 45 therefore shows that the antenna can be matched to achieve the specifications defined in chapter 1.

## 4.6 Verifying the effect of introducing the unconnected monopoles in EMDS

In this section the effect of introducing the unconnected monopoles into the model in EMDS will be explored. This is done to verify the assumption made in section 3.1.2, of the possibility of simplifying the model.

In Figure 46 a comparison of matching is shown. It seams that there is a larger difference when simulating with EMDS than with WIPL-D. This difference is quite large and might become a problem for the results discovered with the assumption made in section 3.1.2. However one can also observe that the reflection factor becomes about the same for both cases. This leads to that the VSWR of the antenna should be about the same for both cases.

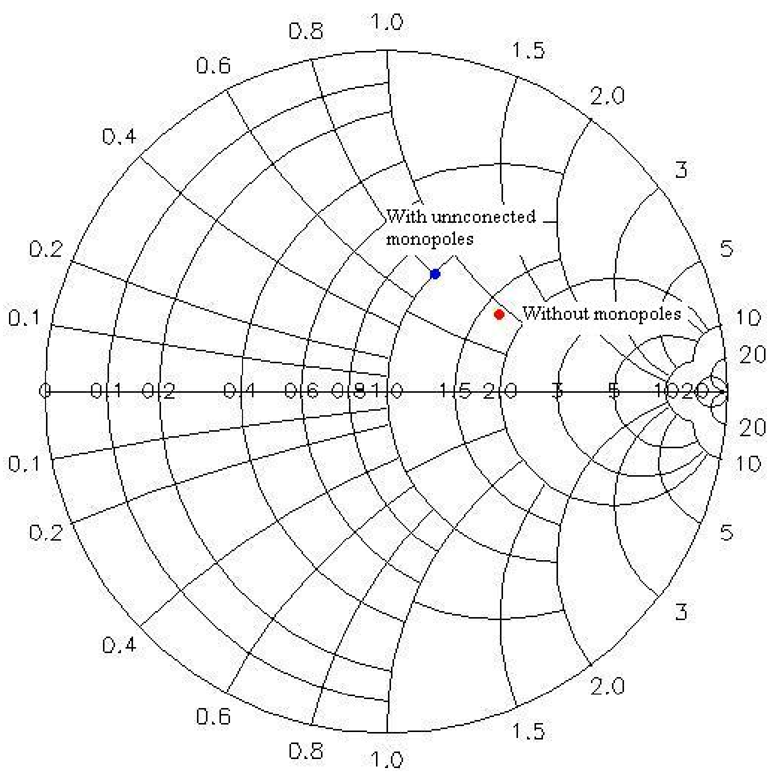


**Figure 46 Smith chart with and without the unconnected monopoles**

In Figure 47 the radiation characteristics are shown. From this figure it can be concluded that the extra monopoles does not have a large effect on the radiation characteristics. It is concluded that for the purpose of this thesis this is still a good enough approximation since it is the radiation characteristics that is the most important factor. This will be measured in section 5.4.

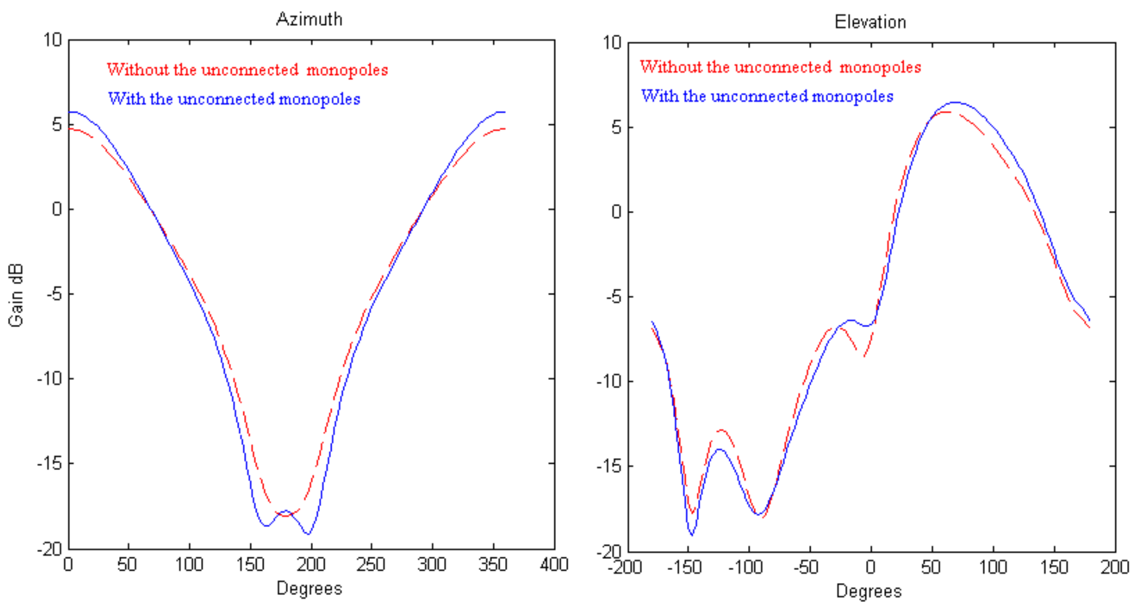


**Figure 47 Difference in radiation characteristics**

# 5 Testing of the prototype

In this chapter the results of the testing of the constructed prototype will be presented. The prototype was built by “Teleteknisk verksted” at NTNU Trondheim. It consists of a circular ground plane made of aluminum with detachable monopoles made of brass around the active monopole. All of the six parasitic monopoles in the picture in Figure 48 are threaded down in to the ground plane. But as can be seen from the picture three of them is threaded directly in to the ground plane and three is isolated. This isolation can be seen as the white parts around the monopoles to the left in Figure 48. The center active monopole is also exchangeable by disconnecting the connector and removing the whole monopole with its connector. Three different lengths of the parasitic and active monopoles have been made.

These are:

Parasitic:

- 37 millimeters
- 39 millimeters
- 41 millimeters

Active:

- 33 millimeters
- 35 millimeters
- 37 millimeters

These lengths have been chosen with background in the results in chapter 3 and 4.
The ground plane has a radius of 75 mm or half a wavelength and the skirt is a quarter wavelength or 37.5 mm.

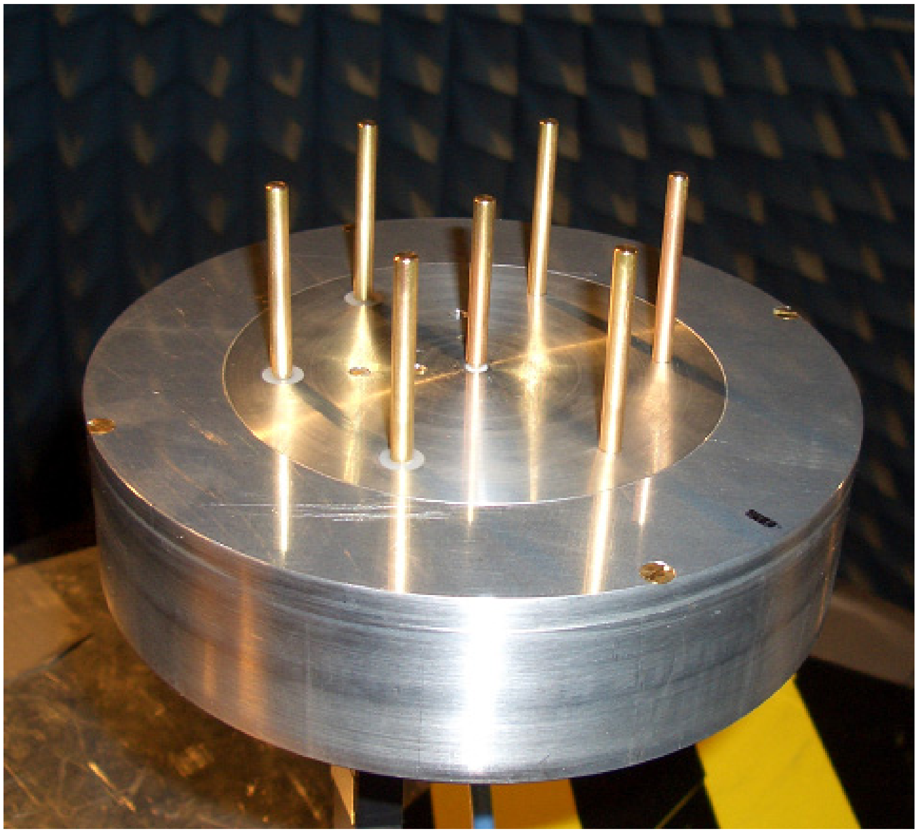

**Figure 48 Picture of the prototype**

**Figure 49 Details of the active monopole**

Regarding the matching of the antenna the prototype was built without any form of matching scheme. This is done to simplify the construction of the antenna. In addition the radiation characteristics of the antenna are a more important factor than the matching. The matching result will mainly be presented for comparison between the different measurements and not as much for comparison with simulations. There is a slight difference between the simulated model and the prototype. In the simulations a connector with a 4 mm center conductor was used.

For practical reasons in the prototype there were used a 1 mm inner conductor.
This results in dielectric diameter of about 3.5 mm. This is narrower than the width of the monopole that is to be connected. Therefore the active monopole was made with a slanting bottom end as shown in Figure 49. These differences should not have too much effect on the radiation characteristics of the antenna. But this will probably have an effect on the matching of the antenna.

There will be conducted measurements with all the nine different combinations of monopole lengths. In addition there will be conducted measurements with a larger ground plane beneath the antenna as to simulate the roof of a car. This situation is illustrated in the picture in Figure 50. Notice that the stand the antenna is mounted on, is of a non conducting material.

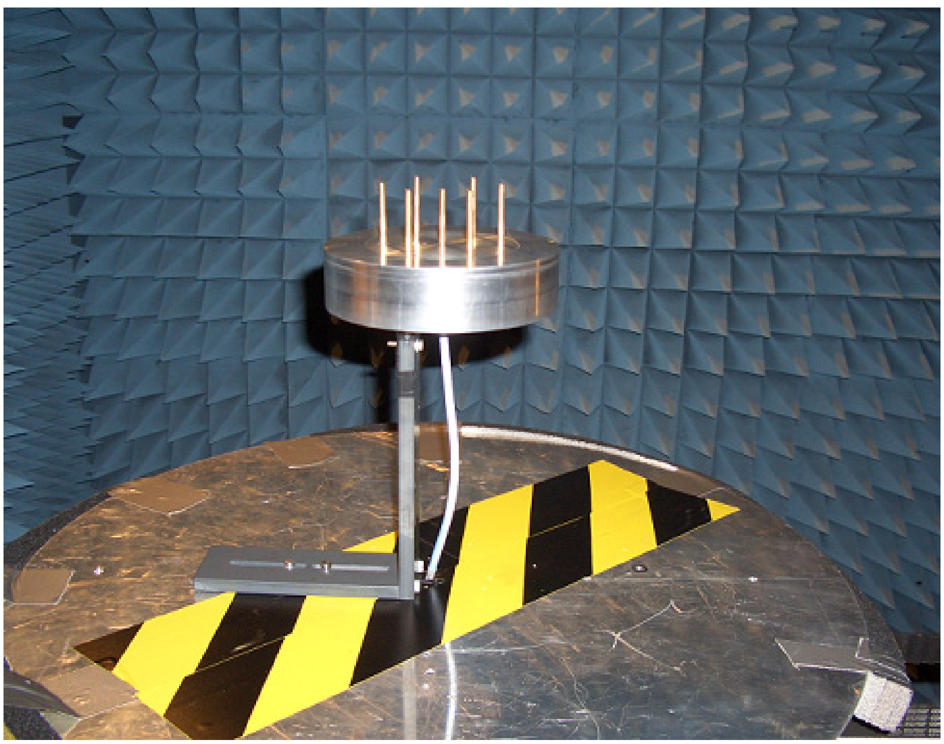

**Figure 50 Large ground plane**

The situation with an active monopole length of 35 mm and parasitic lengths of 39 mm will be explored most thoroughly since it was the configuration that was decided to be the best solution under the simulation work. The radiation diagrams are in this chapter normalized for better to compare the different cases.

## 5.1 With only active monopoles

These measurements are presented mostly as a basis for calculations of gain for the preferred solution in section 5.3.1. But also to explore eventual causes for inaccuracies, due to the production of the antenna.

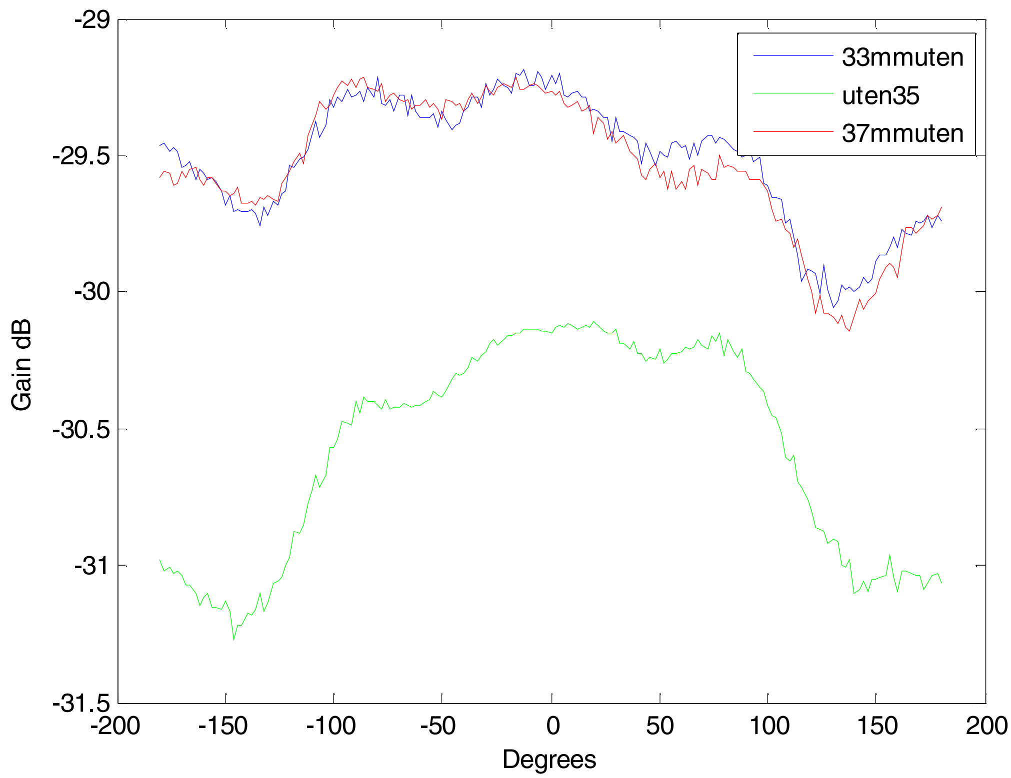


**Figure 51 Azimuth radiation**

From Figure 51 the loss from the transmitter antenna to the produced antenna can be seen. It also seams that there is a slight increase in gain in the preferred radiation direction. This is probably because of the isolated parts of the antenna. These differences in gain are however very small. It can also be observed that it is in fact the preferred length of 35 mm that has the lowest gain. But again this is by a very small degree. For the cases with an active monopole length of 33 and 37 mm no gain calculations will be presented. This since the beam width and back to front ratio is more important. There is also difficult to calculate the gain because of the high mismatching in the antenna configurations and the many uncertainties that occurs in such a setup.

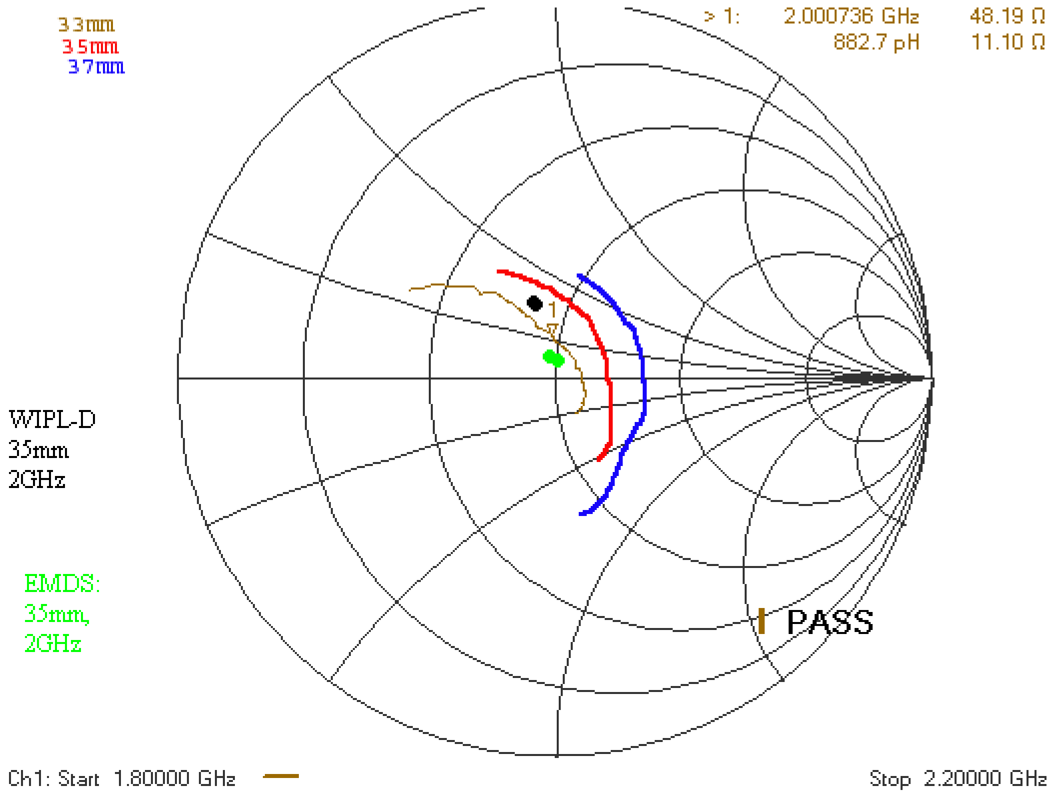


**Figure 52 Smith chart**

As can be seen from Figure 52 the matching of the antenna is best for the lowest active monopole. It can be observed that there is a significant difference in the matching of the antenna from the measured results to the simulated results. This was expected because of the construction of the antenna as mentioned in the beginning of this chapter.

## 5.2 Height of active monopole: 33 mm

Figure 53 shows a smith chart for the different lengths of the parasitic monopoles. The matching is very poor. A large difference from the simulations was expected as explained in the beginning of this chapter. One thing that can be observed is that the matching becomes slightly worse the higher the monopoles get. This is the opposite of the results exhibited in Table 2, but again the matching of the produced antenna might not be accurate because of the construction of the antenna as described in the start of this chapter.

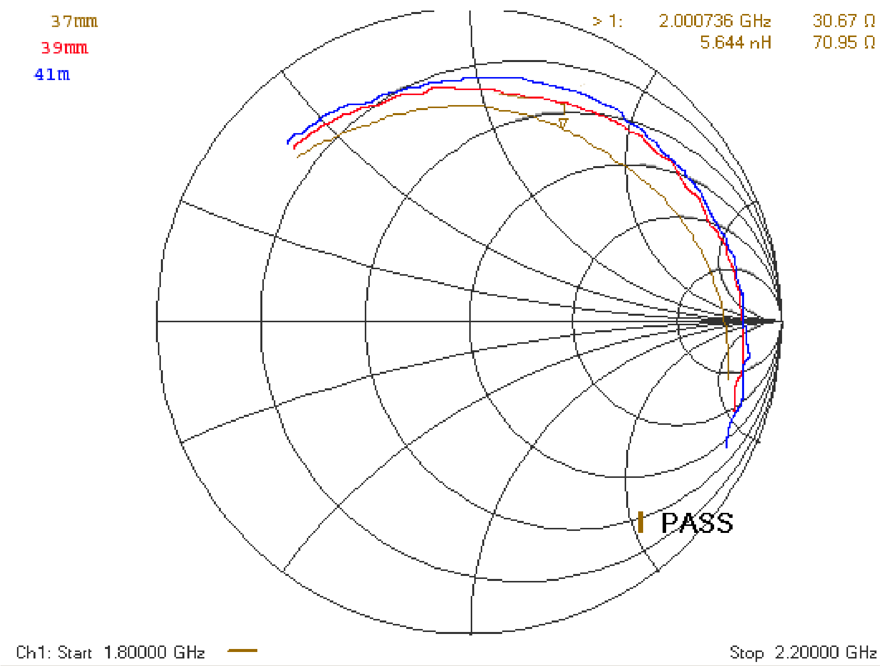


**Figure 53 Smith chart**

From Figure 54 and Figure 55 it can be observed that it is actually the configuration with the lowest monopoles that exhibit the best radiation characteristics. It has the narrowest beam width and the lowest backwards radiation. This is also the exact opposite result as discovered in Table 2. This leads towards that the simulation results are inaccurate for this case. It should be mentioned that the cases summarized in Table 2 are with an active monopole height of 35 mm and this might have an effect on the radiation characteristics.

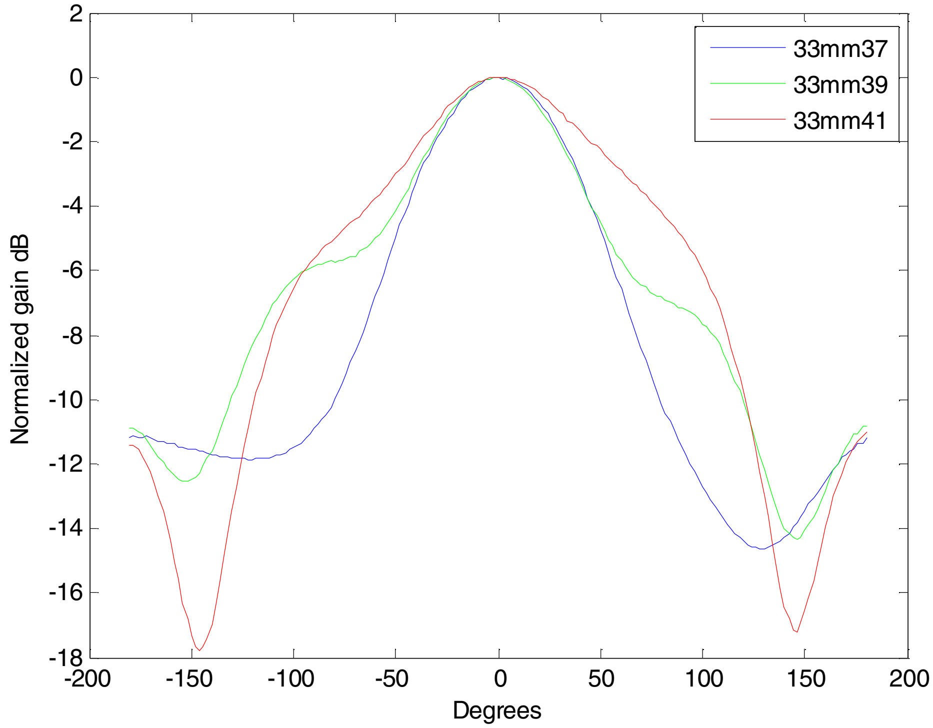


**Figure 54 Azimuth radiation**

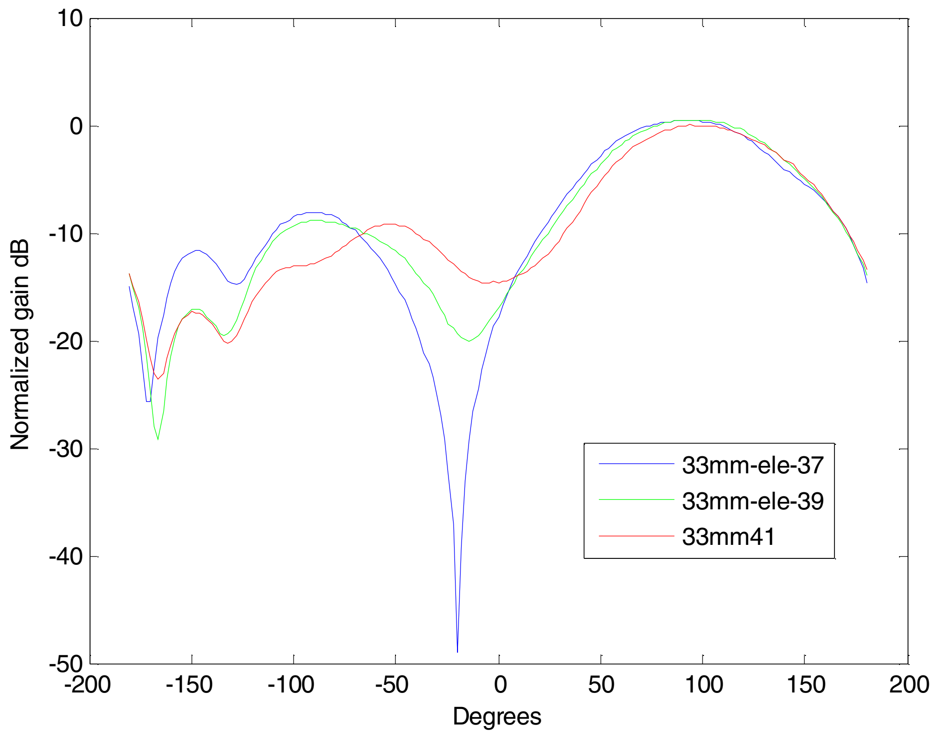


**Figure 55 Elevation radiation**

## 5.3 Height of active monopole: 35 mm

This section will be a bit more extensive than the sections describing the other lengths of the active monopoles. This is because the preferred case from the simulations will be measured in this section. As can bee seen from Figure 56, the matching characteristics exhibits the same properties as for the previous case. In Figure 56 the Smith chart measured with only the three connected monopoles in place are also shown as a green line. It seams that these three extra monopoles have a lot more to say than the simulations showed. But the antenna still exhibit much worse matching characteristics than the simulations indicate.

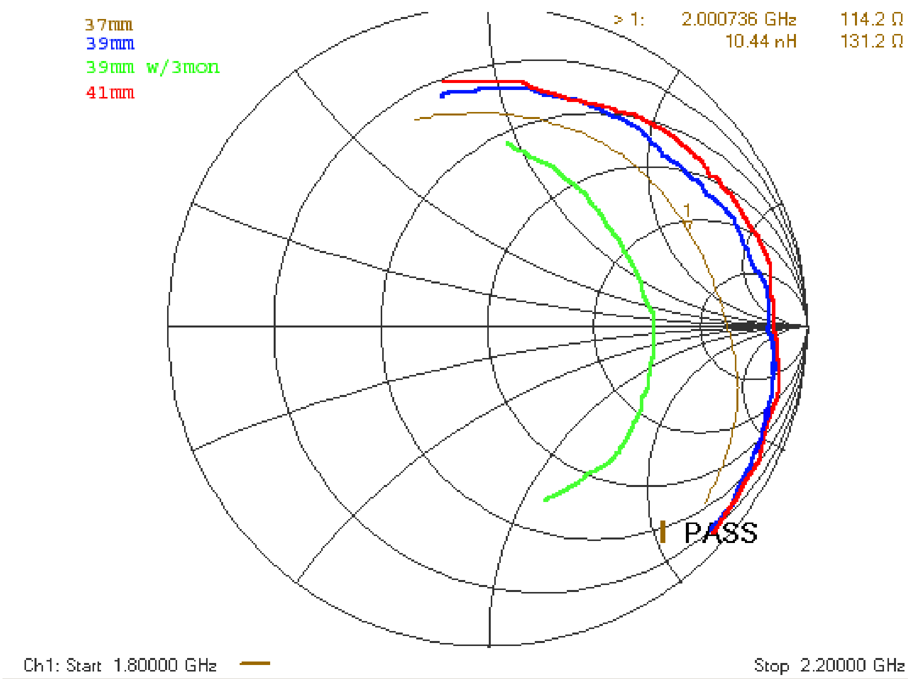


**Figure 56 Smith chart**

In Figure 57 and Figure 58 the radiation characteristics are shown. Again it can be observed that the shorter the parasitic monopoles are the better the radiation characteristics get. It is again obvious that the best radiation characteristics are obtained with a parasitic monopole length of 37 mm.

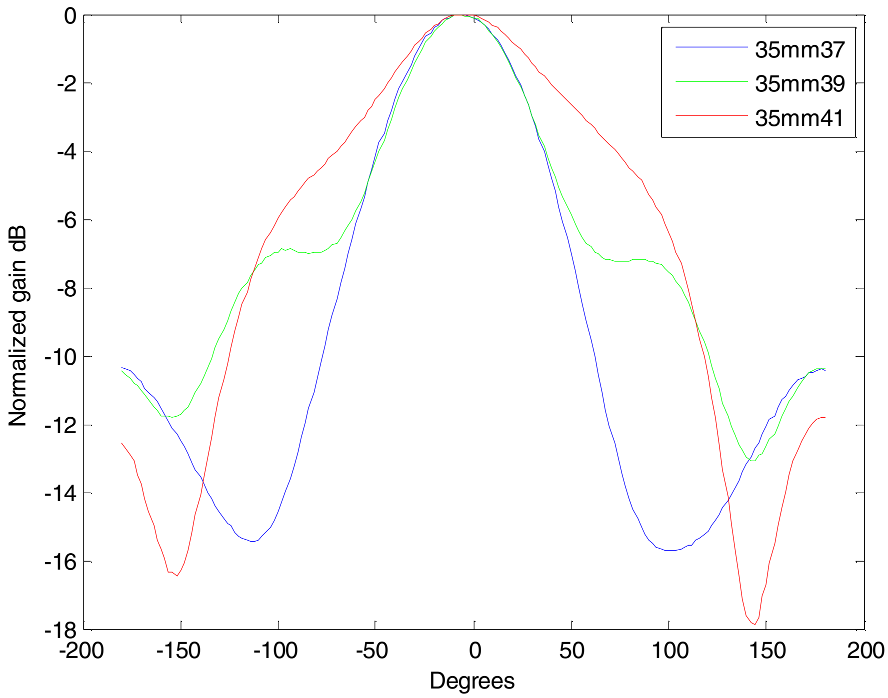


**Figure 57 Azimuth radiation**

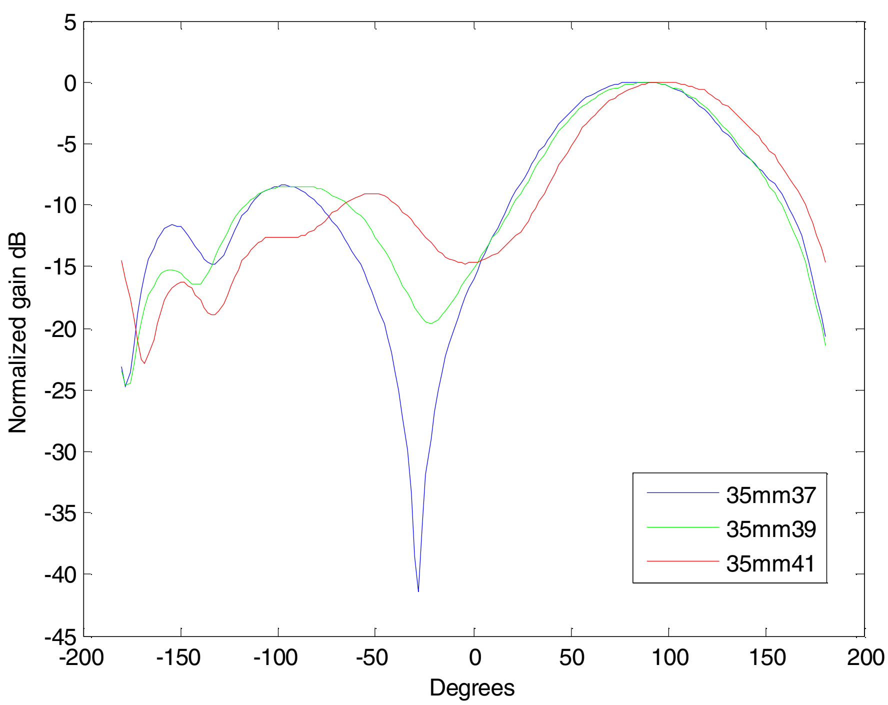


**Figure 58 Elevation radiation**

Another thing that can be observed as a major difference from the simulations is the elevation angle of the radiation. The elevation angle is about 0 degrees (the 0 degrees mark in the figures are the horizontal direction) for all cases described in this chapter. This is a large improvement from the simulations where the elevation angel was about 20-25 degrees. This is very useful since the antenna is thought to be used as a communication device between cars and radiation in the vertical direction is preferred as described in chapter 1. For the case with 41 mm high parasitic monopoles the radiation actually has its maximum below the level of the ground plane, this is also seen for the previous case but not to such a degree.

### 5.3.1 Gain

From Figure 4 it can be observed that the antenna has a simulated gain of about 1.8 or about 2.5 dB. Since this is a very simple structure to simulate this value is thought to be accurate enough to use in these calculations. The simulated value of the gain is used for simplicity and because of the amount of uncertainties in the measurements setup.

The antenna was calibrated at the point of mounting such that the values measured is the values the antenna actually gives out with the given input power. Figure 51 shows the received power without the parasitic monopoles. For the case of 35 mm this level is about -30.5 dB. When taking in to consideration the 2.5 dB gain of the antenna the received signal power of the tested antenna is about -33 dB. The gain will only be calculated for the situation with 39 mm parasitic monopoles, but the same method can be used for the other configurations using the information in the appendices and Figure 51.

The formula that can be used for calculating gain is:

$$G = P_R - P_M + G_{mon} + L_{Rf} \qquad \textbf{Equation 1}$$

$G$ = Gain of the antenna
$P_R$ = Power received from the output of the antenna
$P_M$ = Power measured of single monopole in according to Figure 51
$G_{mon}$ = Gain of the single monopole, according to Figure 4
$L_{Rf}$ = Reflection loss, according to the

For the situation with 39 mm high parasitic monopoles, Equation 1 gives a gain of about 9.5 dB, which is about 2 dB higher than the simulated results presented in Table 2. Again it should be mentioned that this is a calculation with many possible inaccuracies and should be seen upon as an estimate.

### 5.3.2 Comparing simulated radiation characteristics with measured radiation

In this section the measured results will be compared with the results simulated in both softwares. In Figure 59 and Figure 60, both the case with 37 mm and 39 mm parasitic monopoles are presented. This because of the results presented in the beginning of this section, where the case with 37 mm parasitic monopoles was found to be the best configuration. The simulations were made with an active monopole length of 35 mm.

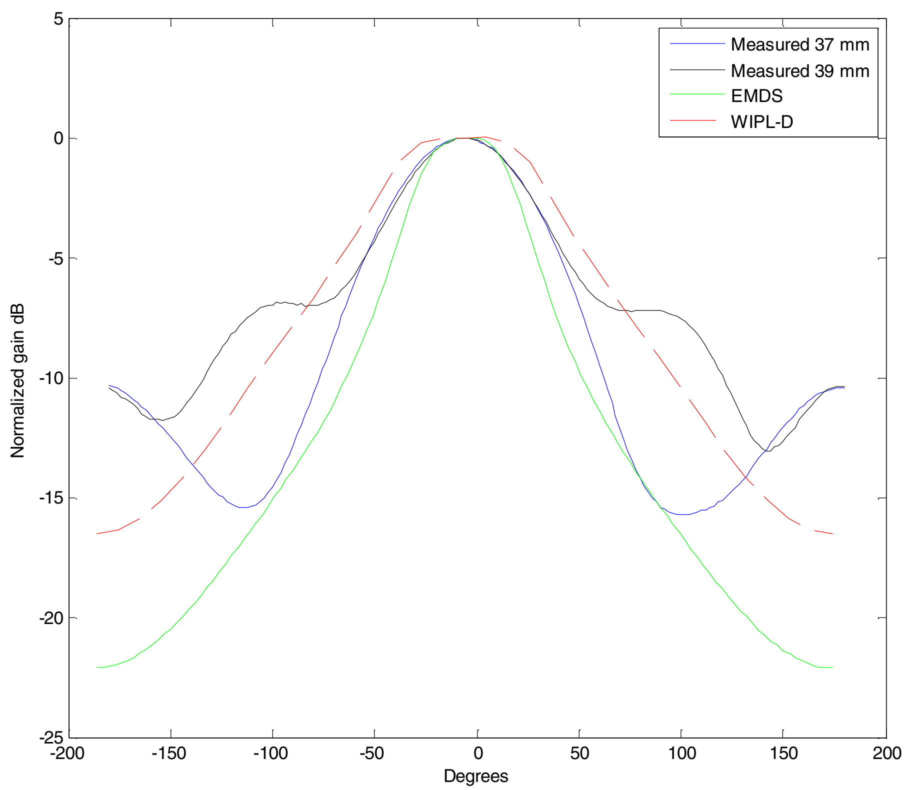


**Figure 59 Azimuth radiation**

Figure 60 shows, that the simulations in EMDS are the more optimistic of the two softwares simulations. It also shows that the two measured results lie between the two simulated results regarding the beam width. And the measurements lie above both the simulations regarding the backward radiation. But it is EMDS that overall provides the most accurate results for the azimuth radiation characteristics. The largest difference is that the backwards radiation is much larger for the measured results than for the simulated results. Both the situation with 37 mm and 39 mm have the same half power beam width  and the same backwards radiation but the sideways radiation is significantly larger for the case with 39 mm parasitic monopoles. This can indicate that the solution with 37 mm high parasitic monopoles is the closest to the simulated results with 39 mm heights.

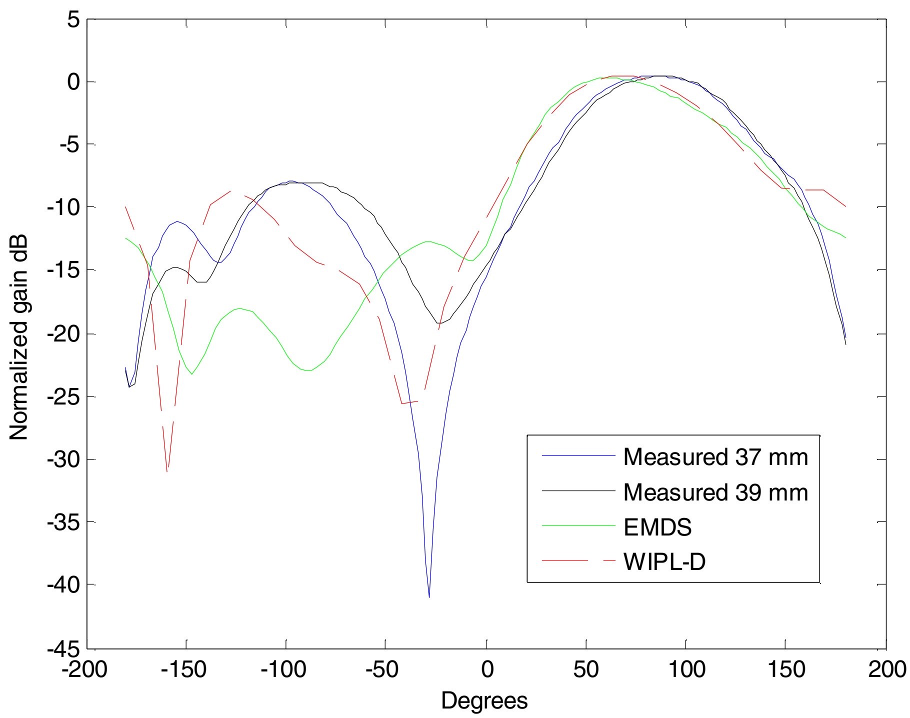


**Figure 60 Elevation radiation**

Figure 60 shows the previously mentioned difference that the elevation angle of the radiation is about 25 degrees lower for the measured results than for the simulated results. For the elevation radiation characteristics it is actually WIPL-D that is the most accurate. This undermines slightly the assumption that EMDS is the most accurate software. Both softwares agree to some extent on the radiation characteristics in the preferred direction.

## 5.4 Height of active monopole: 37 mm

This section will consider the case with a center monopole of 37 mm. This configuration shows much of the same properties and progress that the previous cases exhibit. Thus the differences between the various lengths of the parasitic monopoles will not be commented further. The matching is illustrated as a Smith chart in Appendix 1. The radiation characteristics are illustrated in appendices 2 and 3.

However at this configuration an extra measurement was made. The effect of removing the unconnected parasitic monopoles from the antenna has on the radiation characteristics. Simulations of this effect were made in section 4.6.

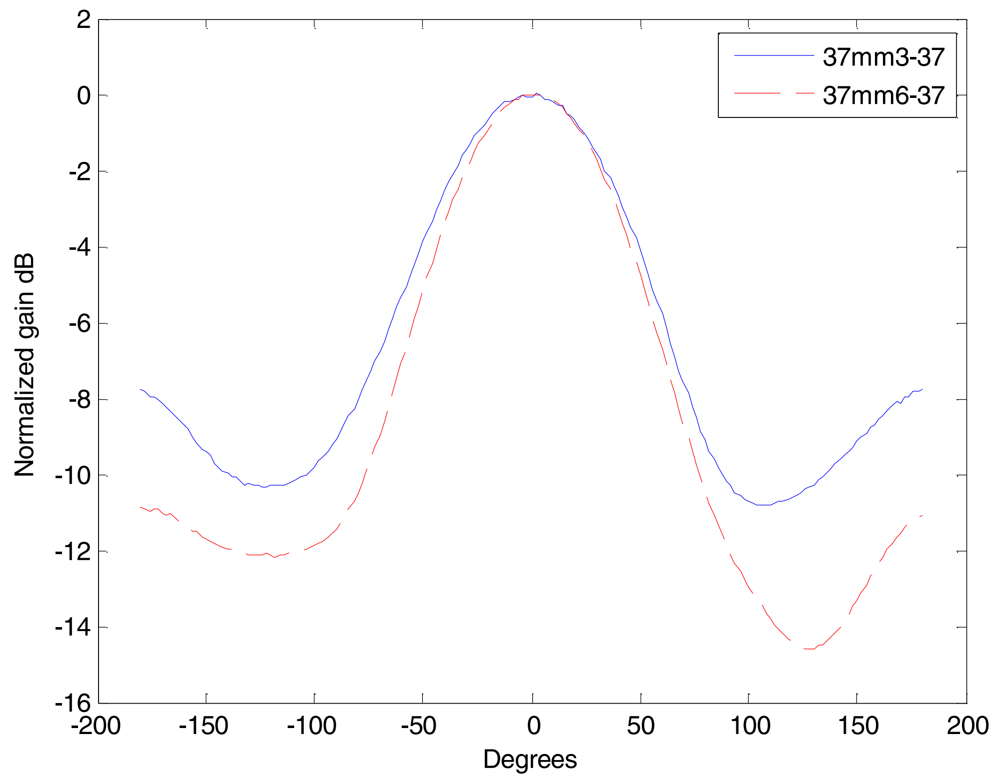


**Figure 61 removing the extra three unconnected monopoles**

As can be seen from Figure 61 removing the monopoles from the antenna has a certain effect. 37mm3-37 indicates that the active monopole is 37 mm and that there are three parasitic monopoles of 37 mm each. The beam width gets wider when removing these monopoles. This can indicate that the unconnected monopoles act as a kind of directors. However this is not the same effect that was simulated. Figure 47 shows that the opposite effect occurs under simulations of the same case. This goes into the line of effect that is reversed from simulation work to the measured results.

## 5.5 Testing the antenna above a larger ground plane

Because this antenna is thought to be used for communications between cars it is important to investigate how the radiation characteristics are affected by a large ground plane beneath the antenna.

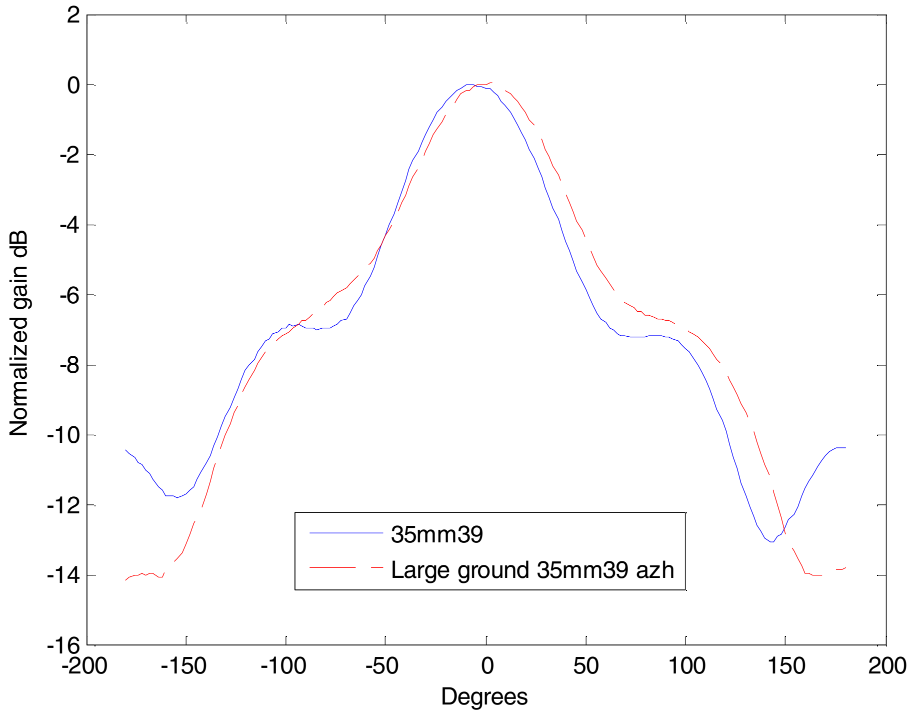


**Figure 62 Azimuth radiation**

As can be seen from Figure 62 the larger ground plane does not affect the azimuth radiation of the antenna to any significant degree.

But as can be seen from Figure 63 the elevation radiation is greatly affected by this. The course of the radiation in the different directions is mainly the same but it fluctuates much more then without the ground plane. However the back to front ratio is about the same and as can be observed the radiation is actually lower for most of the backward section.

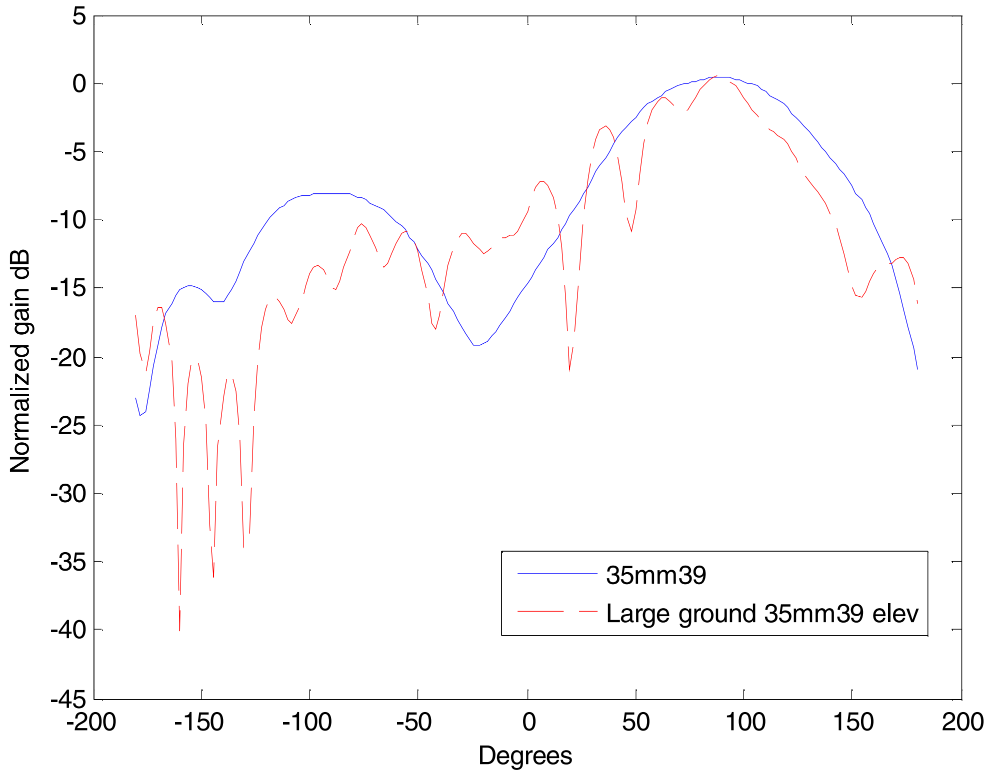


**Figure 63 Elevation radiation**

The forward radiation is a bit worse and uneven but still has its maximum in the vertical plane. It should be noted again, as mentioned in the beginning of this chapter, that the antenna was mounted on to the ground plan with a non conducting material. The height the antenna was mounted above the ground plane was about 20 cm. See Figure 50 for illustration of the mounting.

## 5.6 Summary of the measurements

In this section a table of the results presented in this chapter will be displayed.

| Active monopole length | Parasitic monopole length | Measurements | | | | Simulations | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | HPBW | FTBR | El. Angle | VSWR | HPBW | FTBR | El. Angle | VSWR |
| 33 mm | 37 mm | 80 | 12 dB | 0 | 5.3 | - | - | - | - |
| 33 mm | 39 mm | 80 | 12 dB | 0 | 7.4 | - | - | - | - |
| 33 mm | 41 mm | 100 | 12 dB | -5 | 11.8 | - | - | - | - |
| 35 mm | 37 mm | 80 | 12 dB | 0 | 5.6 | 85 | 11 | 25 | 3.8 |
| 35 mm | 39 mm | 80 | 11 dB | 0 | 7.8 | 90 | 16 | 25 | 3.5 |
| 35 mm | 41 mm | 100 | 13 dB | -10 | 11.8 | 100 | 21 | 25 | 3.2 |
| 37 mm | 37 mm | 80 | 12 dB | 0 | 5.5 | - | - | - | - |
| 37 mm | 39 mm | 80 | 12 dB | 0 | 7.9 | - | - | - | - |
| 37 mm | 41 mm | 120 | 16 dB | -10 | 12.4 | - | - | - | - |

**Table 4 Summary**

HPBW = Half power beam width in degrees

FTBR = Front to back ratio in dB

El. Angle = Elevation angle in degrees above the vertical plane

VSWR= Voltage standing wave ratio

As can be seen from Table 4 the physical measurements do not vary as much between the different monopole lengths, as the simulated ones. The measured result is better regarding the half power beam width but worse at the front to back ratio. The VSWR is also substantially worse for the measured results, but the probable reason for this is explained further in the start of this chapter.

# 6 Conclusion

This thesis has described the design and testing of an ESPAR antenna solution for the use of communication purposes between cars. The ESPAR antenna consists of a circular ground plane with a skirt mounted around the ground plane. Many different configurations have been simulated.

The variations simulated were:

- The number of passive monopoles and the angle between them
- The radius and height of the monopoles
- The height of the skirt and the radius of the ground plane
- Matching schemes

From the simulations made in this thesis it was concluded that an antenna with a total of seven monopoles were chosen to be the best solution. One active in the middle and six spaced equally around the active monopole. The distance from the active monopole to each of the passive monopoles was set at 37.5 mm or a quarter wavelengths. The preferred radius of the ground plane was found to be half a wavelength or 75 mm and the height of the skirt was set to a quarter wavelengths. With an active monopole length of 35 mm and a parasitic monopole length of 39 mm the antenna behaves within the radiation specifications described in chapter 1. The half power beam width was simulated to be about 90 degrees and the front to back ratio was found to be 16 dB. The half power beam width is a bit higher than ideal but it proved difficult to improve this much further. One other specification that should be mentioned is that the matching of the antenna was quite poor. A matching scheme to improve this are described in section 4.3. It was found that the antenna could be matched to fulfill the requirements made in chapter 1. Detailed results of the different configurations can be found in Table 1 and Table 2.

Two different softwares were used for simulations on the antenna. WIPL-D was used for early simulations since this is a fast software. EMDS was used mainly for matching schemes since it has more possibilities to make complex structures, but is very slow. However these two programs presented quite a lot of differences in some of the results, especially on the matching characteristics of the antenna. This is discussed in detail in chapter 4.

On the basis of the simulated results a prototype was made. This prototype was made with three isolated parasitic monopoles and three monopoles connected directly to the ground plane. A picture of the prototype is shown in Figure 48. The prototype was made with three different lengths of all the monopoles. 33 mm, 35 mm and 37 mm for the center active monopole, and 37 mm, 39 mm, and 41 mm for the parasitic monopoles were produced. The lengths of these were chosen while considering the simulated results. No matching scheme was implemented because it is the radiation properties that are the most important characteristics, and the matching should not have an effect on the radiation pattern of the antenna. The radius of the ground plane and the height of the skirt is the same as the on decided to be the best from the simulation work.

While testing on the prototype several differences was discovered from the simulated work. One preferable difference was that the elevation angle went from about 25 degrees in the simulations to about 0 degrees in the measurements. But the matching of the antenna was measured to be much worse than simulated. This however is probably related to the minor differences made form the simulated model to the constructed antenna and is discussed further in chapter 5. One other difference that was discovered was that the antenna behaves in the reverse way when varying the length of the parasitic monopoles. The higher the monopoles get the narrower the beam width, which is the opposite of the effect found by simulations. But it should be mentioned that these differences in radiation characteristics was less in the measured results than in the simulated results.

The best measured configuration was found to be with an active monopole of 35 mm and parasitic monopoles with a length of 37 mm. This antenna had a half power beam width of about 80 degrees and a front to back ratio of about 12 dB. Detailed results can be found in Table 4.

# 7 References


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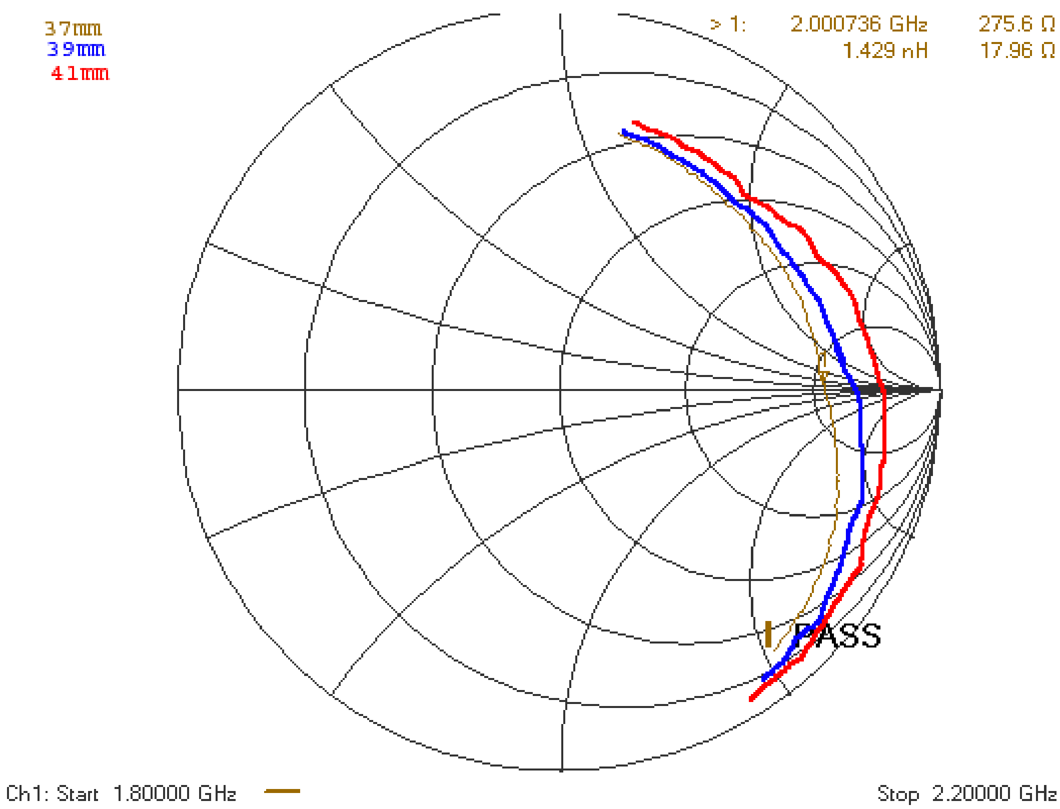
# 8 Appendices

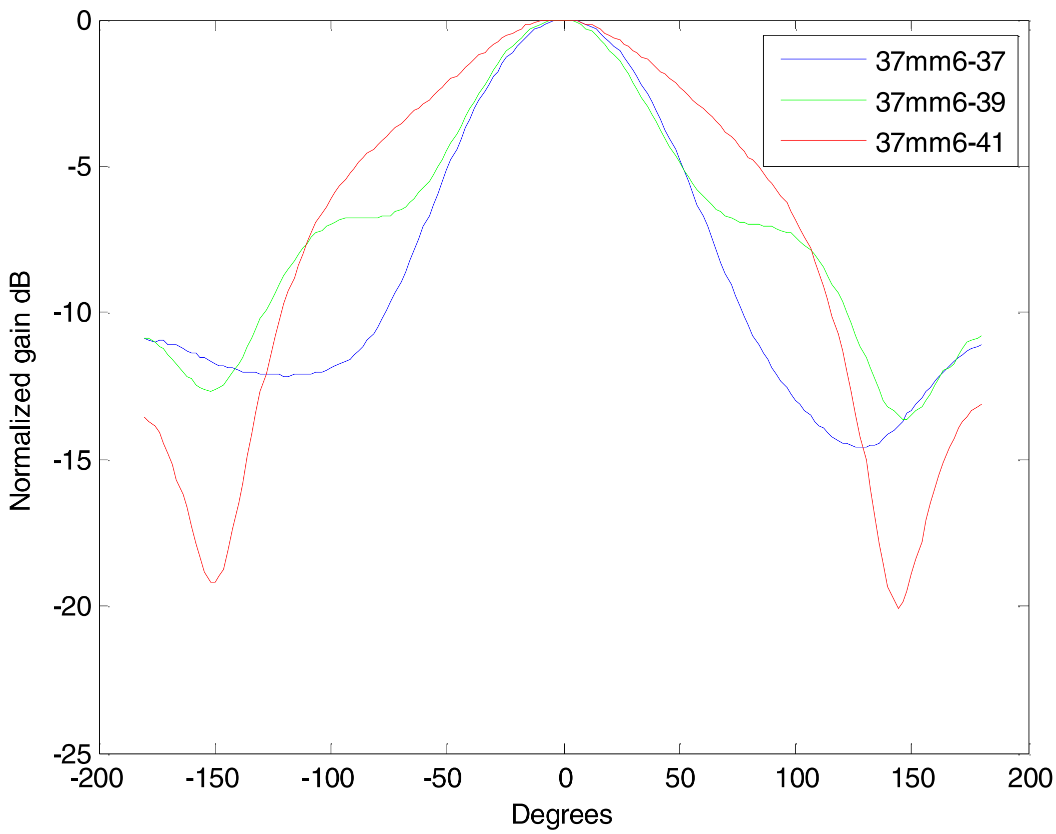
## Appendix 1

Smith chart for the 37 mm active monopole case



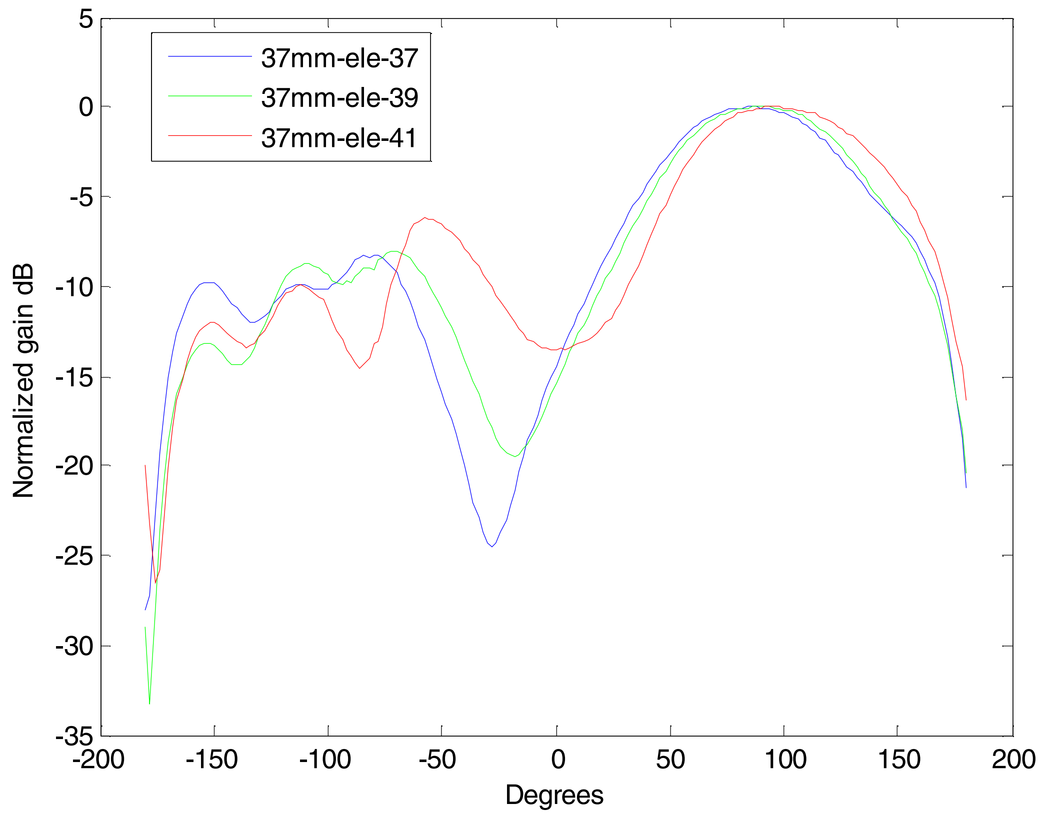
## Appendix 2

Azimuth radiation characteristics for the 37 mm active monopole case



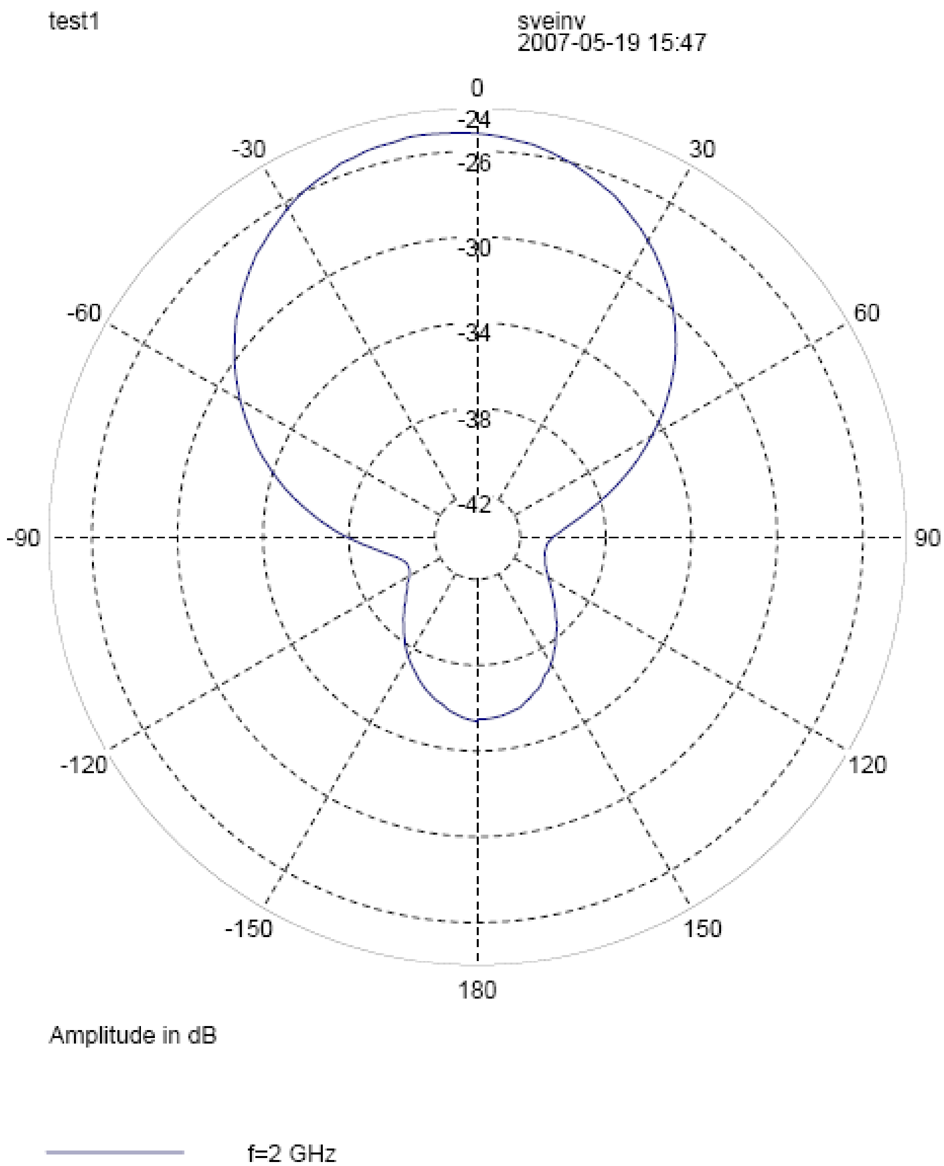
## Appendix 3

Elevation radiation characteristics for the 37 mm active monopole case



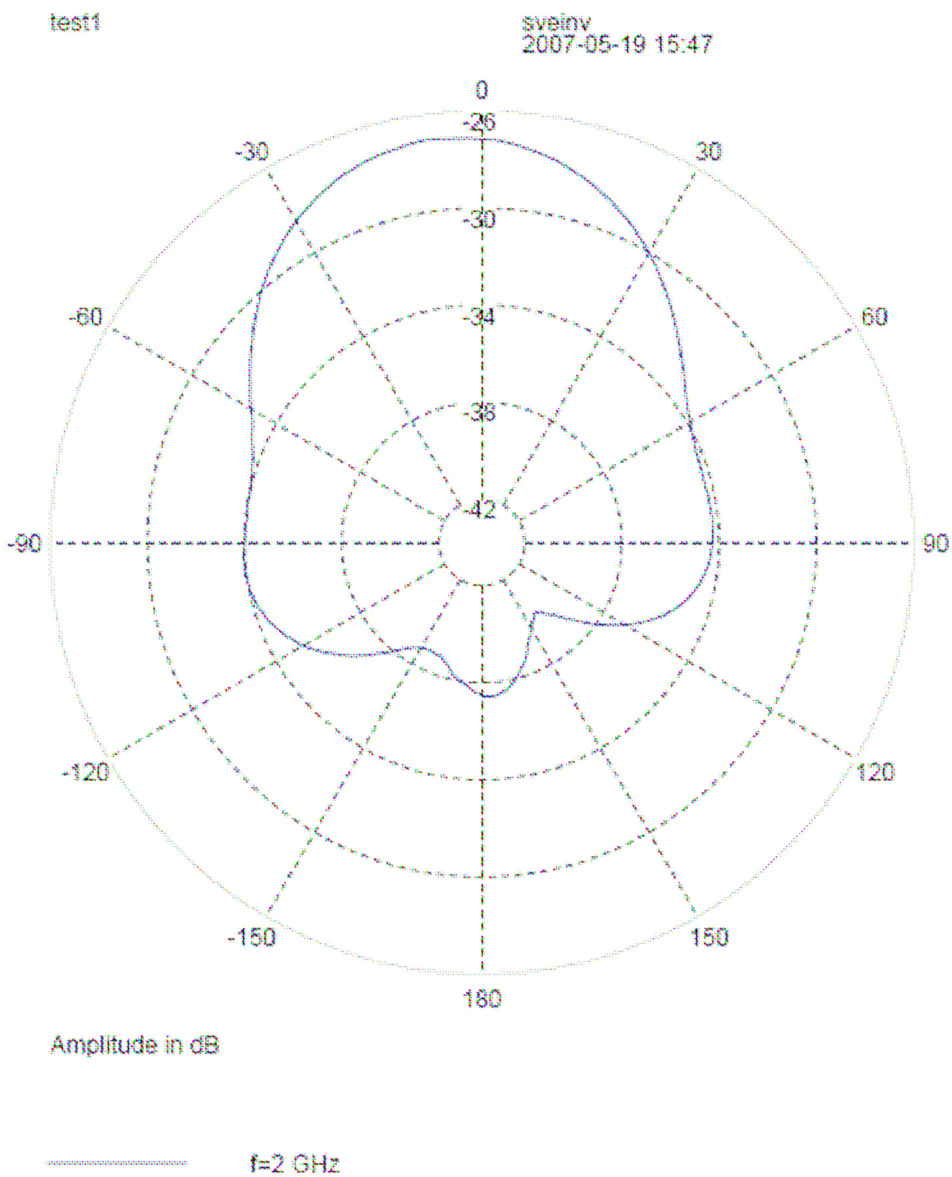
## Appendix 4

Azimuth radiation
35 mm active
37 mm parasitic



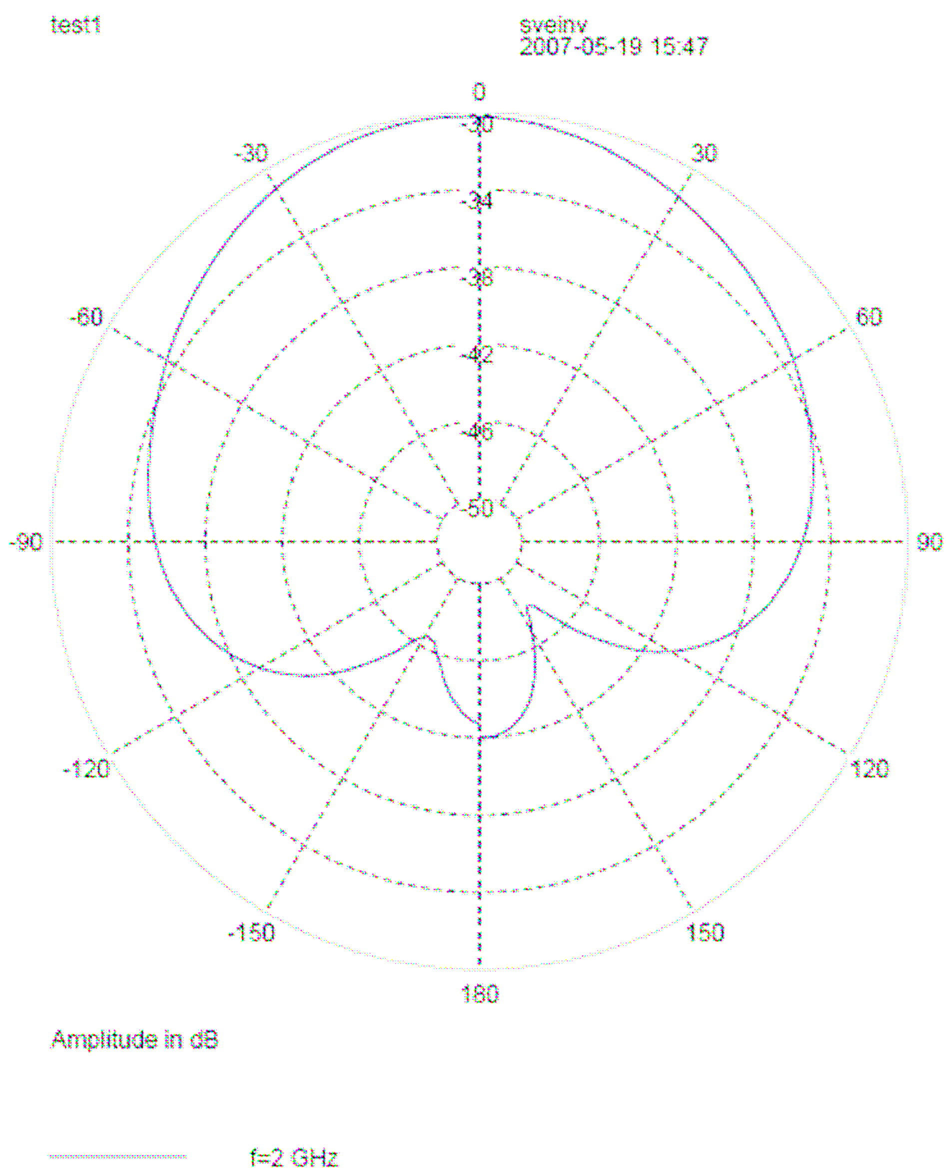
# Appendix 5

Azimuth radiation
35 mm active
39 mm parasitic



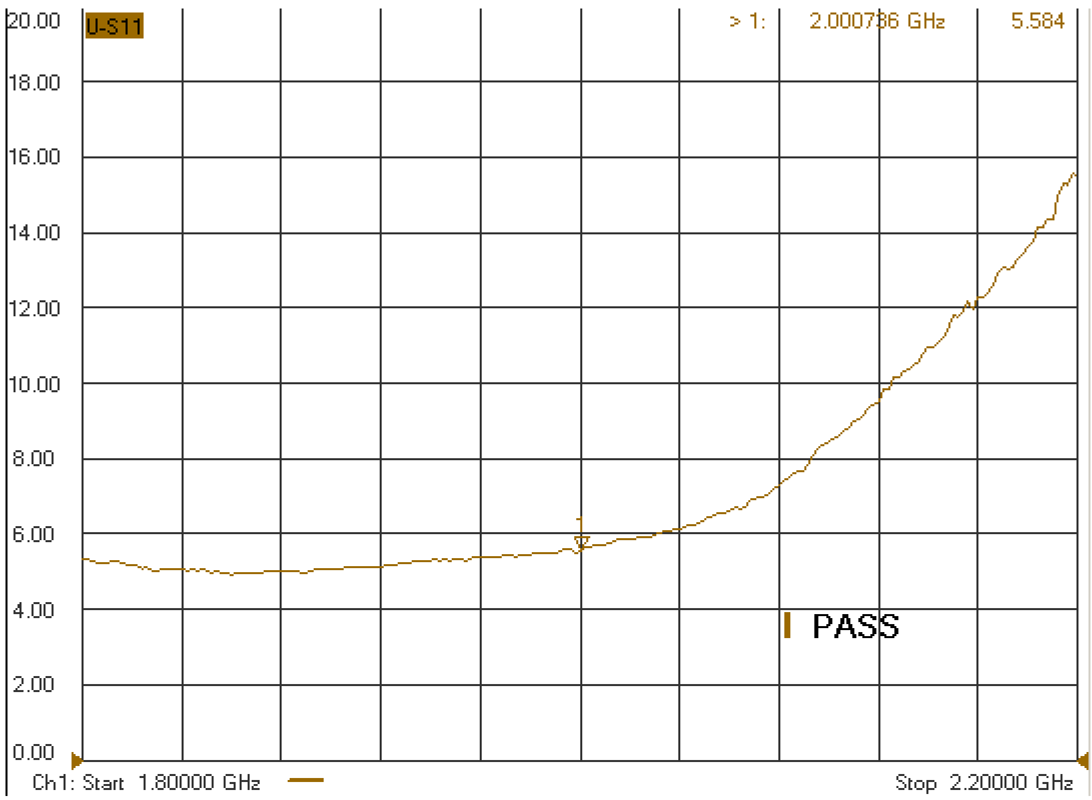
# Appendix 6

Azimuth radiation
35 mm active
41 mm parasitic



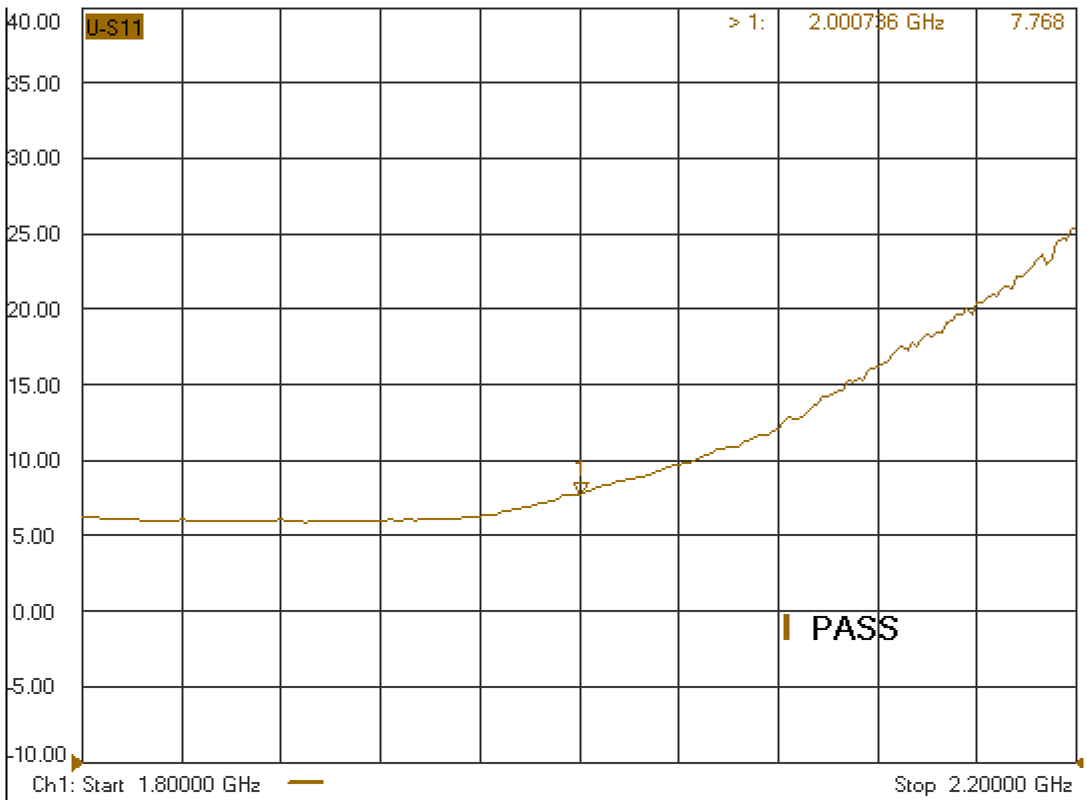
# Appendix 7

VSWR
35 mm active
37 mm parasitic



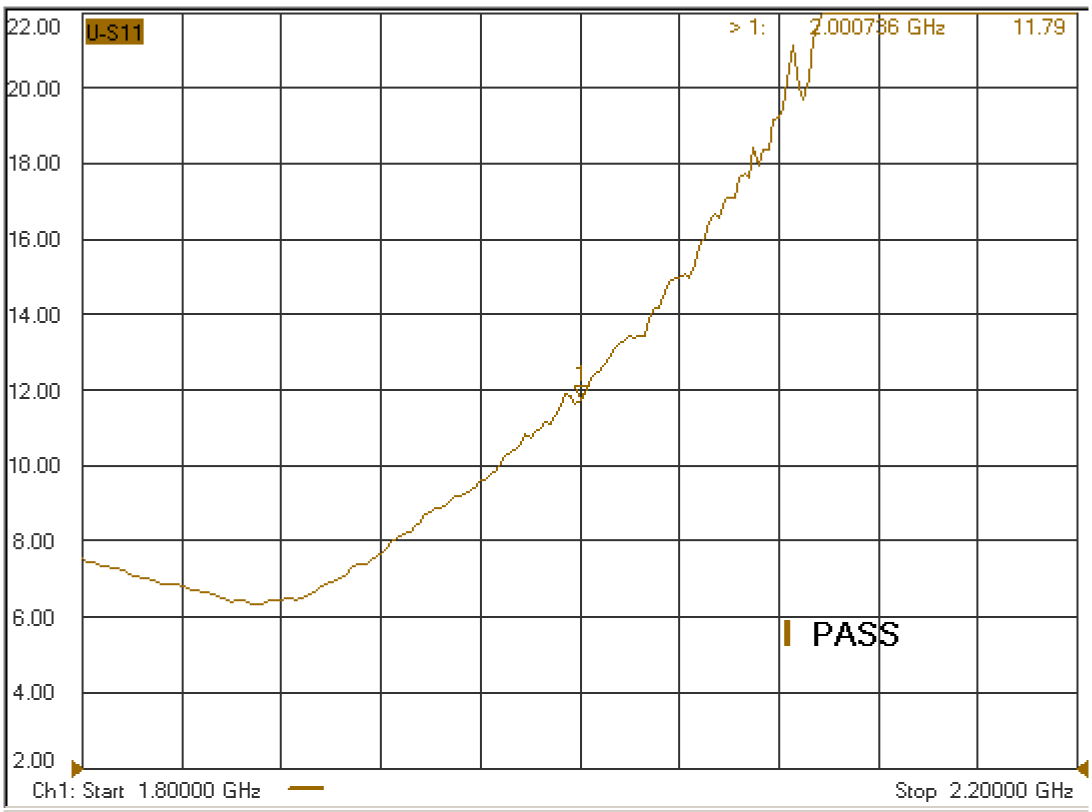
## Appendix 8

VSWR
35 mm active
39 mm parasitic



## Appendix 9

VSWR
35 mm active
41 mm parasitic



# Appendix 10

VSWR conversion table

| Return Loss - dB | SWR | GAMMA | Reflection Loss - dB | Through Power - % | Reflected Power - % |
|---|---|---|---|---|---|
| 1 | 17.39 | 0.891 | 6.868 | 0.206 | 0.794 |
| 2 | 8.72 | 0.794 | 4.329 | 0.369 | 0.631 |
| 3 | 5.85 | 0.708 | 3.021 | 0.499 | 0.501 |
| 4 | 4.42 | 0.631 | 2.205 | 0.602 | 0.398 |
| 5 | 3.57 | 0.562 | 1.651 | 0.684 | 0.316 |
| 6 | 3.01 | 0.501 | 1.256 | 0.749 | 0.251 |
| 7 | 2.61 | 0.447 | 0.967 | 0.800 | 0.200 |
| 8 | 2.32 | 0.398 | 0.749 | 0.842 | 0.158 |
| 9 | 2.10 | 0.355 | 0.584 | 0.874 | 0.126 |
| 10 | 1.92 | 0.316 | 0.458 | 0.900 | 0.100 |
| 11 | 1.78 | 0.282 | 0.359 | 0.921 | 0.079 |
| 12 | 1.67 | 0.251 | 0.283 | 0.937 | 0.063 |
| 13 | 1.58 | 0.224 | 0.223 | 0.950 | 0.050 |
| 14 | 1.50 | 0.200 | 0.176 | 0.960 | 0.040 |
| 15 | 1.43 | 0.178 | 0.140 | 0.968 | 0.032 |
| 16 | 1.38 | 0.158 | 0.110 | 0.975 | 0.025 |
| 17 | 1.33 | 0.141 | 0.088 | 0.980 | 0.020 |
| 18 | 1.29 | 0.126 | 0.069 | 0.984 | 0.016 |
| 19 | 1.25 | 0.112 | 0.055 | 0.987 | 0.013 |
| 20 | 1.22 | 0.100 | 0.044 | 0.990 | 0.010 |

[8]