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Passive and Electronically Steered Array Planar Feeds for Satellite Communications

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Passive and Electronically Steered Array Planar Feeds for Satellite Communications

Kyle C Browning

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

Passive and Electronically Steered Array Planar Feeds
for Satellite Communications

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As the need for more bandwidth increases, satellite communication (SatCom) terminals are forced to climb higher in frequency. Higher frequency means greater propagation losses, and so antenna gain and sensitivity have to increase. The higher the gain, the more difficult it is to point the antenna. To make matters even more challenging, consumers are requesting satellite links in harsher environments and on moving vehicle and planes. In order to meet today’s challenges and improve on dish feeds, research is ongoing to replace fixed-beam feedhorns with smaller, cheaper, and lighter PCB based antennas and to develop low-cost electronically steered array feeds (ESAF). ESAFs will not only improve the signal link, but they will also aid in pointing the antenna and then tracking the satellite independent of movement.

Here is presented some of the first planar antenna dish feeds developed by the Brigham Young University’s SatCom Group. Included are the simulation and test procedures to determine if they are viable for SatCom use. The results show that these antennas make significant advancements in efficiencies and prove a path forward to a feedhorn replacement. Several planar designs are presented, each with a unique solution to meet all the requirements for a dish feed.

Also presented is the first low-cost ESAFs developed to give commercial SatCom an electronically steerable dish. None of the designed hardware requires a redesign of current modems and receiver boxes. The research looks at keeping costs low by minimizing the required electronics. This further led to researching the limits on how simple the electronics could be. The ESAF doubled the visible area of the dish and successfully acquired and tracked a satellite as the dish moved. The ESAF also demonstrates a path forward to increase the steerable range and improve pointing and tracking.

Keywords: array feeds, electronically steered array feeds, satellite communications, beamforming
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Chapter 1

Introduction

1.1 Satellite Communication

A wireless link can communicate over long distances and reach multiple users. It eliminates the costly need to run cables to every system on the network and provides a way to communicate when cabling is not possible. Wireless links are limited by line-of-sight, attenuation, and noise. Satellites were introduced to overcome some of these limitations. One satellite can reach millions of users without anything blocking the link. An earth based antenna pointing at a satellite has a clear line-of-sight and picks up mostly sky noise which has the lowest natural noise contribution. The major disadvantage is the attenuation loss because satellites operate great distances from Earth and this loss increases with frequency.

The $K_u$ Band is one of three frequency bands primarily dedicated to commercial satellite communication (SatCom). The band is used for very small aperture terminal (VSAT) (Downlink: 11.7-12.2 GHz and Uplink: 14.0-14.5 GHz), direct broadcast satellite (DBS) (12.2-12.7 GHz) and Free-to-Air (FTA) (11.7-12.2 GHz) systems. $K_u$ band has a good balance between antenna gain and attenuation loss. The higher gain allows satellites to be placed closer together without increasing co-interference, compared to older L and C band satellites. Also, since effective area increases with frequency, the users can use a smaller receive antenna without sacrificing the link quality. However, due to extra attenuation losses, the transmit and receive antennas must perform very well to have sufficient signal to noise ratio (SNR) for a data communication link.
1.2 Planar Antennas and Array Feeds for SatCom

The most common antenna platforms for SatCom are symmetric and offset dishes. Dishes are reflectors that require another antenna (feed), facing the dish, to receive or produce the reflected energy. Dishes can offer high gain and low sidelobes.

The most common commercial feed for a dish is the horn antenna (feedhorn). The feedhorn is very efficient and over the years has become very cheap to produce. Two major drawbacks with feedhorns are that they are large, requiring waveguide and a transition to a circuit board, and their beam patterns are narrow so they only operate well on certain dish sizes.

Planar antennas are capable of addressing the feedhorn drawbacks. The design of planar antennas allows them to be small, fitting on the same board as the receiver electronics, and to be fed directly without a wave guide transition. They also can be designed to have very narrow to very wide beam patterns, working for a wide range of dish sizes.

Horn and planar feed antennas are passive and fixed beam antennas. They can only have one satellite link per dish without using multiple feeds. They only point in one direction without the aid of a mechanical system to steer them, which are expensive, bulky, and slow. Passive antennas are limited in their applications. If the dish operates in a environment where it will move quickly, such as high winds or vibrations on a moving vehicle, the mechanical system will not be able to maintain a good link with the satellite. Over time the satellite’s orbit decays and the satellite will begin moving outside of its intended location making it hard to track and maintain a good link.

Active array feeds allow the dish beam to steer electronically. They are much faster than a mechanical system and provide enough range of motion to compensate for and track movement from both the Earth based dish and the satellite. Active arrays also allow for improvements in the link quality and for multiple beams, allowing several different satellite links from one feed.
1.3 Previous Work

This work investigates two areas: commercial SatCom for antennas in motion and enhancements to dish antennas. A large portion of the research done in these two areas can be summarized by the following examples.

1.3.1 Planar Aperture Arrays for SatCom

Planar aperture arrays can achieve the same gain as dish antennas, and are smaller, lighter, and flat. This makes them ideal for mobile applications where antennas must have low profiles. [1] represents some of the first work on planar arrays for SatCom; however, it was designed as a fixed antenna and mobile applications require steerable antennas.

Boeing Connexion was an electronically steered aperture array. The array panel would mount on top of planes and track satellites as the planes flew below, giving passengers satellite TV and internet. The system was deemed too costly and did not get the expected customer base. It was only implemented on a few planes [2, 3].

Because of the expense of implementing a full electronically steered array, research has been done to drop the cost by developing hybrid mechanical aperture arrays. KVH TracVision A7 uses a mechanical system to do all the pointing and an array to skew a fixed beam, allowing the panel to lay almost flat [4]. [5] uses a mechanical system to adjust azimuth and 1D electronically steerable array for elevation pointing. Both of these systems are good, but they are still expensive and limited by the mechanical steering speed.

This work is different than existing aperture arrays because the dish reflector is used to achieve the required gain, allowing the array feeds to be much smaller and still steer the antenna. Smaller arrays reduce the complexity of the antenna and the number of required components.

1.3.2 Planar Antenna Feeds

Traditionally, planar antennas are not used as feeds because they have low efficiencies; however, substrate materials and simulation software are improving, allowing planar antennas to be designed specifically as high performance feeds. [6] and [7] are among the first to
publish on using microstrip antennas as reflector feeds, but this is not a heavily researched area because of planar antenna performance.

Brigham Young University's (BYU) SatCom group specializes in building planar antenna feeds and has found solutions to improve planar antennas so that they can be used as SatCom feeds [8, 9]. Some of the group's research is presented in this work.

1.3.3 Electronically Steered Array Feeds

Electronically steered array feeds (ESAF) are not widely researched for commercial applications. These feeds are very complicated and very expensive, but they allow beam steering without moving the dish. Also, ESAFs provide an important blend of high gain dish antennas and adaptive beamforming.

[10] began the early research of beam steering without moving the dish ([11] discusses more about the feed). Today, ESAF research is done mainly in the radio astronomy community where they are called phased-array feeds (PAF). [12] is an example of a PAF.

The signals of interest in radio astronomy are at incredibly low levels, so feeds must perform very well. The BYU Radio Astronomy group is one of the leading experts in the area of PAFs. They have developed PAFs for several radio telescopes [13, 14, 15]. Each antenna is designed to have very low loss and contribute as little noise as possible to the system.

Radio astronomy PAFs also incorporate many beamforming techniques to be able to detect the signal. [16], [17], and [18] are just some samples of the research that has gone into understanding PAFs characteristics and performance, and how to implement array beamforming on a dish feed.

The research performed by the BYU Radio Astronomy group provides the theoretical background for ESAF SatCom design; however, the PAFs and beamforming systems are far too expensive for SatCom use [19]. A major focus of this work is simplifying the PAF systems to create a low-cost ESAF. This can be done because, unlike radio astronomy, SatCom signals have higher SNR. Also, this work requires that antenna elements be planar, and that they and the beamformer be placed on the same board.
1.4 Thesis Contributions

This work makes the following contributions...

- Introduces high efficiency, planar feed antennas that have comparable performance to a feedhorn.
- Covers the design of a low-cost ESAF.
- Provides new ideas to simplify array beamformer electronics, including, removing conventional beamforming electronics and simplifying excitation currents.
- Demonstrates that a low-cost ESAF is feasible and that it can maintain a link independent of motion.

1.5 Thesis Outline

Chapter 2: Background
Contains the necessary theory, equations, and geometry to understand this work and continue into the future work.

Chapter 3: Planar Feed Antenna
Introduces several planar feed antenna designs for feasible feedhorn replacements and the testing process for simulation and measurement. These designs are more compact and can be placed directly on the same board as the receiver electronics. Also, gives simulated and measured results that show that these antennas have high efficiencies and SNR to be able to compete with feedhorns.

Chapter 4: Designing an ESAF
Covers the design process of two different ESAF, the trade offs, and ways to bring down the cost while still meeting requirements. Includes an in depth study of beam weights and how to simplify beamformer electronics.
Chapter 5: Testing the ESAF

Establishes the test procedure and setup of the ESAF. Discusses the calibration process and how to control the array. Gives the measured results and compares them to simulation. Demonstrates tracking ability with a dish in motion.

Chapter 6: Conclusion

Closing statements of this work as well as future work that can be done to improve dish feeds, ESAFs, and satellite tracking.
Chapter 2

Background

2.1 Antennas Analysis

Antennas are devices that transform between waves on a transmission lines and waves in space. From a RF circuit point of view, they are matching networks that matches the transmission line impedance to the wireless environment impedance. These two perspectives provide a way to analyze antennas using how they match the transmission line and how radiated waves, or fields, are shaped by the antenna. The fields around the antenna and the antenna impedance can be found using Maxwell’s equations.

2.1.1 Far Fields

The the far fields radiated by an antenna can be found using the radiation integral which is derived from the Helmholtz equation, Green’s functions, and several other equations and mathematical principles. This derivation requires two approximations; that the antenna will be in a homogeneous space and that it will operate electrically far from the point of interest. The approximations are known as free space and far field, respectively [20, 21]. The far field equations are

\[
\vec{E}(\vec{r}) = jk \frac{e^{-jkr}}{4\pi r} \left[ \hat{\theta}(-\eta N_\theta - L_\phi) + \hat{\phi}(-\eta N_\phi - L_\theta) \right],
\]

\[
\vec{H}(\vec{r}) = jk \frac{e^{-jkr}}{4\pi r} \left[ \hat{\theta}(N_\phi - L_\theta / \eta) + \hat{\phi}(-N_\phi - L_\phi / \eta) \right],
\]

\[
\vec{N}(\vec{r}) = \int e^{jk\vec{r} \cdot \vec{r}'} \vec{J}(\vec{r}') \, d\vec{r}',
\]

\[
\vec{L}(\vec{r}) = \int e^{jk\vec{r} \cdot \vec{r}'} \vec{M}(\vec{r}') \, d\vec{r}'.
\]
$k$ is the wavenumber, $\eta$ is the wave impedance, $r$ is the distance between the antenna and the observer, $\hat{r}$ is a unit vector that defines the direction of the observer, and $\bar{r}'$ is the variable of integration over the antenna. $\bar{J}(\bar{r}')$ and $\bar{M}(\bar{r}')$ represent equivalent current and magnetic sources of the antenna. These sources can be solved analytically for simple antennas, but for most antennas these sources are found through a numeric solver.

The following two sections contain definitions, equations, and theory from the IEEE standards for antennas [22] and [21].

2.1.2 Antenna Parameters

*Radiation Pattern* $(f(\theta, \phi))$ is defined as angular power distribution radiated by an antenna. It is the angular dependent portion of the power density.

*Power Density* radiated by an antenna is the time average power of $\bar{E}(\bar{r})$ and $\bar{H}(\bar{r})$. It is expressed as

$$\bar{S}_{av}(r, \theta, \phi) = \frac{1}{2} \text{Re}[\bar{E}(\bar{r}) \times \bar{H}(\bar{r})^*] = \frac{|\bar{E}(\bar{r})|^2}{2\eta} \hat{r} \quad (2.5)$$

$$\simeq f(\theta, \phi) \frac{1}{r^2} \hat{r}, \; r \to \infty.$$  

*Directivity Pattern* is the ratio of the power density radiated by an antenna to the power density radiated by an isotropic radiator with the same total power. The total power radiated by an antenna is

$$P_{rad} = \oint_S \bar{S}_{av} \cdot d\bar{S} \quad (2.6)$$

where $S$ is a surface that encloses the antenna. The power density of an isotropic radiator is $\bar{S}_{iso} = \frac{\hat{r} P_{rad}}{4\pi r^2}$. Therefore, by definition, directivity pattern is

$$D(\theta, \phi) = \frac{S_{av}(\bar{r})}{P_{rad}/(4\pi r^2)}. \quad (2.7)$$

Often for antennas the directivity, the peak value of its directivity pattern, is used instead of directivity pattern. There is an approximate inverse relationship between directivity and beamwidth.
Radiation Efficiency is the ratio of the power radiated to power into the antenna port as follows

$$\eta_{rad} = \frac{P_{rad}}{P_{in}}$$  

(2.8)

The idea comes from modeling an antenna with two resistors, one that accounts for the power radiated out and the other that counts for the power lost in the antenna. A lossless antenna has a radiation efficiency of 1.

Gain is similar to directivity, but instead of relating power density to total radiated power it relates power density to total power delivered to the antenna. This accounts for losses in the antenna.

$$G(\theta, \phi) = \eta_{rad} D(\theta, \phi).$$  

(2.9)

2.1.3 Receive Antenna Parameters

Receive Open Circuit Voltage is the voltage received by an antenna given an incoming wave if there is no load on its port (network theory can be used to reference loaded circuit to open circuit voltage). Open circuit voltage is found by analyzing an antenna as a receiver using a incident plane wave coming toward the antenna and the reciprocity principle of antennas, which gives the relationship between transmit and receive patterns of an antenna. The result is

$$V_{oc} = \frac{1}{I_0} \frac{4\pi jre^{jkr}}{\omega \mu} E^{inc} \hat{p} \cdot \vec{E}^t(\vec{r})$$  

(2.10)

where $\vec{E}^t$ is the field radiated by the antenna as if it were a transmitter excited with the current $I_0$. $\vec{E}^t$ is evaluated in the direction looking towards the incident wave at a distance $r$, which represents the distance between true transmitter and receiver. $\hat{p}$ is the polarization of the incident wave.

Received Power is the power delivered to the receiver from the antenna. The simplest expression for receive power assumes a conjugate matched load. It is expressed as

$$P_{rec} = P_{in} G_t G_r \eta_{pol} \left( \frac{\lambda}{4\pi r} \right)^2$$  

(2.11)
where \( \eta_{pol} = |\hat{p}_t \cdot \hat{p}_r| \) is the polarization efficiency, \( G_r \) is the gain of the receive antenna in the direction of the transmitter, and \( G_t \) is the gain of the transmit antenna in the direction of the receiver. \( P_{in} \) is the power sent to the transmit antenna. For SatCom, \( P_{in}G_t \), is often combined in one term called equivalent isotropic radiated power (EIRP).

Signal to Noise Ratio is the most important figure of merit for a communication system receiver and is defined as ratio of the received signal power to the received noise power. A common way to evaluate noise power is using thermal noise generated by a resistor at a temperature \( T \). The power in this thermal noise is defined by \( P_N = k_B T B \), where \( k_B \) is the Boltzmann’s constant and \( B \) is the system bandwidth. Receiver system noise can be modeled as having a temperature \( T_{sys} \), which is the equivalent temperature a resistor must reach in order to generate the same noise as the system. Using equation (2.11) and \( T_{sys} \), the signal to noise ratio (SNR) is defined as

\[
\text{SNR} = \frac{\lambda^2 P_{in}G_tG_r\eta_{pol}}{(4\pi r)^2 k_B BT_{sys}}.
\] (2.12)

The system temperature can be broken down into each contributing factor using

\[
T_{sys} = \eta_{rad}T_a + (1 - \eta_{rad})T_p + T_{rec}
\] (2.13)

where \( T_p \) is the physical temperature of the antenna, \( T_a \) represents the external noise temperature from the environment that the antenna picks up, and \( T_{rec} \) is the equivalent noise temperature of the amplifiers and other electronics attached to the antenna.

2.2 Dish Antennas

Dish antennas are a type of aperture antenna. Aperture antennas must be excited with a propagating field that is produced by another antenna. In the case of a dish, the excitation antenna is called the feed and is located such that fields from the feed reflect off the dish. The performance of the dish depends on the way the feed illuminates the dish surface. To characterize dish antenna performance, aperture and spillover efficiency are added to the above mentioned parameters [21, 23, 24].
**Aperture Efficiency** is defined by the ratio of the directivity to the standard directivity. The standard directivity is the max directivity of a planar aperture of the same physical area \((A_p)\) as the antenna when excited by a uniform plane wave. If the aperture is larger than the wavelength, then aperture efficiency is

\[
\eta_{ap} = \frac{\lambda^2}{4\pi A_p} D. \tag{2.14}
\]

**Spillover Efficiency** accounts for all the power that is not distributed on the dish surface. It is defined as

\[
\eta_{sp} = \frac{P_{illum}}{P_{feed}} \tag{2.15}
\]

where \(P_{illum}\) is the power on the dish surface and \(P_{feed}\) is the total power radiated by the feed.

Using these efficiencies, gain from equation (2.9) becomes

\[
G = \eta_{rad}\eta_{ap}A_p\frac{4\pi}{\lambda^2} \tag{2.16}
\]

and from equation (2.13), \(T_{sys}\), using the fact that SatCom dishes point towards the sky, becomes

\[
T_{sys} = \eta_{rad}(1 - \eta_{sp})T_{ground} + \eta_{rad}T_{sky} + (1 - \eta_{rad})T_p + T_{rec}. \tag{2.17}
\]

### 2.3 Antenna Arrays

An active antenna array uses closely spaced elements with controllable excitation currents to achieve a desired radiation pattern. An array employs many degrees of freedom that are not found in a passive antenna. The array designer has the ability to choose the elements (which do not have to all be the same), number of elements, element spacing, and excitation currents. Not only can the pattern be designed to almost any shape, but controlling the excitation currents electronically allows the pattern to change shape without having to change the elements or the physical layout. The array, therefore, can adapt for maximum SNR, maximum gain, interference cancellation, or multiple beams. The disadvantage of an array is the complexity and cost of the design.
To fully control the array, the excitation currents must be changed for each element. This means each element must have its own digital signal processing (DSP) unit or bank of variable amplifiers and phase shifters. The array will also need a controller that adjusted the currents as needed. This can be very expensive, so one of the focuses of this work, found in section 4.3, is simplifying the electronics required for max-SNR beamforming using an array feed.

2.3.1 Array Electric Field

An array can be made of different elements with unequal spacing. Arbitrary arrays can be analyzed by defining the field from an element excited by the current $I_0$, with all the other elements in the array open circuit loaded, as $\vec{E}_n(\vec{r})$. These fields are calculated using equations from section 2.1.1 and finding the equivalent current and magnetic sources for the array when the $n$th element is excited. Analytically, this is difficult for arbitrary arrays, so numeric solvers are needed to calculate these fields. Solvers do not always use open loaded ports, so network theory must be used to convert the excitation ports to open circuits.

$\vec{E}_n(\vec{r})$ accounts for both the element pattern and the effects of the other elements in the array. With these fields and phasor excitation currents $I_n$, the array electric field becomes

$$\vec{E}(\vec{r}) = \sum_{n=1}^{N} I_n \vec{E}_n(\vec{r}).$$  \hfill (2.18)

A similar equation can be formed for the magnetic field, but for most far field analysis only electric is required.

Arrays combine principles from both electromagnetics and signal processing. To change the electric field to the signal processing convention, the currents are arranged in a column vector and normalized by $I_0$ and the equation above takes on the form

$$\vec{E}(\vec{r}) = \frac{1}{I_0} \sum_{n=1}^{N} w_n^* \vec{E}_n(\vec{r}) = \frac{1}{I_0} \mathbf{w}^H [\vec{E}_1(\vec{r}) \cdots \vec{E}_N(\vec{r})]^T \hfill (2.19)$$
where
\[
\mathbf{w} = \begin{bmatrix}
  i_1^* \\
  i_2^* \\
  \vdots \\
  i_N^*
\end{bmatrix},
\]
(2.20)
\[
\mathbf{w}
\]
is known as the beam weight vector. All the antenna parameters from section 2.1.2 can be calculated for arrays using this convention.

### 2.3.2 Array Signal Model

A signal model is used for arrays so that the principles of electromagnetics can be applied to signal processing. This allows for convenient array calculations and provides the grounds for adaptive array processing. This model will be applied to the receiving case [21, 25].

**Receive Open Circuit Voltage Vector** is a column vector of the voltages received by each element. From equation (2.10) the open circuit voltage of the \( n \)th element is
\[
v_{oc,n} = \frac{4\pi j r e^{jkr}}{\omega \mu I_0} E_{inc} \hat{p} \cdot \vec{E}(\vec{r}).
\]
(2.21)
Arranging \( v_{oc,n} \) in a column vector leads to
\[
\mathbf{v}_{oc} = \frac{4\pi j r e^{jkr}}{\omega \mu I_0} E_{inc} \mathbf{E}_p
\]
(2.22)
where,
\[
\mathbf{E}_p = \begin{bmatrix}
  \hat{p} \cdot E_1(\vec{r}) \\
  \hat{p} \cdot E_2(\vec{r}) \\
  \vdots \\
  \hat{p} \cdot E_N(\vec{r})
\end{bmatrix}.
\]
(2.23)
\[
\mathbf{E}_p
\]
is a convenient way to arrange the element array fields. It is a column vector evaluating each excited element field with the polarization \( \hat{p} \) and the direction, \( \vec{r} \), of the incident plane wave. \( \vec{r} \) is the direction vector of the receive array pointing towards the incoming wave and at a distance \( r \) from the transmitter.
**Receive Voltage Vector** and **Beamformer Voltage Output** are respectively the voltage vector after $v_{oc}$ goes through the electronics and transmission lines before the beamformer and the voltage after the beamformer. The beamformer is DSP unit or electronics and combining network that apply weights and add the signals together. Using a transformation matrix $Q$, which combines the effects of the front end amplifiers, voltage dividers from impedance matching, transmission lines, and other electronics that occur before the beamformer, the receive voltage vector is

$$v = Qv_{oc}. \tag{2.24}$$

And by applying the beamformer, the output voltage is

$$v_{out} = w^H v. \tag{2.25}$$

**Signal and Noise Correlation Matrices** are matrices that can be computed or estimated for both deterministic and random vectors. They contain information about how signals from one element relate to the other elements in the array and are the basis for array signal processing. A correlation matrix is defined as

$$R_x = E[xx^H] \tag{2.26}$$

where $E[\cdot]$ is the expectation operator. The correlation matrix can be estimated using the follow equation and $N$ samples of the random vector

$$\hat{R}_x = \frac{1}{N} \sum_{n=1}^{N} x[n]x[n]^H. \tag{2.27}$$

The receive voltage vector from equation (2.24) includes contributions from signal and noise as follows:

$$v = v_s + v_n. \tag{2.28}$$

Calculating the correlation matrix of the received voltage results in

$$R_v = E[vv^H] = E[v_s v_s^H] + E[v_s v_n^H] + E[v_n v_s^H] + E[v_n v_n^H] = R_s + R_n. \tag{2.29}$$
E[v_s v_n^H] = E[v_n v_s^H] = 0 because v_s and v_n are uncorrelated. $R_s$ is the signal correlation matrix and $R_n$ is the noise correlation matrix. The noise can be further divided into its individual contributions according to

$$v_n = v_{\text{ext}} + v_{\text{loss}} + v_{\text{rec}}.$$  (2.30)

Each contributing noise source is theoretically uncorrelated with each other and so $R_n$ is the sum of the correlations matrices of each source.

**External Noise Correlation Matrix** is the correlation matrix representing the thermal noise received by the antenna due to the brightness temperature distribution $T(\Omega)$ of the surrounding environment. It can be modeled by randomly polarized plane waves coming from all angles. Using this model, equation (2.21) becomes

$$v_{\text{ext,oc},n} = \frac{4\pi jre^{jkr}}{\omega \mu I_0} \int \vec{E}_{\text{ext}}(\Omega) \cdot \vec{E}_n(\vec{r})d\Omega$$  (2.31)

and after applying some principles of black-body radiation, the correlation matrix becomes

$$R_{\text{ext}} = \frac{1}{|I_0|^2} 16 k_B Q A_T(\Omega) Q^H$$  (2.32)

where

$$A_{T(\Omega),mn} = \frac{1}{2\eta} \int T(\Omega) \vec{E}_m(\vec{r}) \cdot \vec{E}_n^*(\vec{r}) r^2 d\Omega.$$  (2.33)

If the external noise is isotropic

$$R_{\text{iso}} = \frac{1}{|I_0|^2} 16 k_B B T_{\text{iso}} Q A Q^H$$  (2.34)

where

$$A_{mn} = \frac{1}{2\eta} \int \vec{E}_m(\vec{r}) \cdot \vec{E}_n^*(\vec{r}) r^2 d\Omega.$$  (2.35)

$A$ is known as the array overlap matrix.

**Array Thermal Noise Correlation Matrix** includes the contributions from both the external noise the array picks up as well as the losses in the array modeled as additive noise.
Array thermal noise is calculated as

\[ R_t = R_{ext} + R_{loss} = 8k_BT_{iso}BQRe[Z_A]Q^H \] (2.36)

where \( Z_A \) is the array mutual impedance matrix of the array.

*Receiver Noise Correlation Matrix* is hard to calculate, but can be estimated with careful measurements. The receiver noise correlation matrix is

\[ R_{rec} = 2BQ[\bar{v}_{R}\bar{I} + Z_A\bar{Y}_c\bar{v}_{R}\bar{I} + \bar{v}_{R}\bar{I}(\bar{Y}_c\bar{I})^HZ_A^H + Z_A\bar{Y}_c\bar{i}_R^2RIZ_A^H]Q^H \] (2.37)

where \( \bar{v}_R \) and \( \bar{i}_R \) are vectors of the equivalent noise voltage and current sources for each receiver chain. \( \bar{Y}_c \) is the correlation admittance between voltage and current noise sources. For satellite receivers and most well designed communication systems the receiver noise is approximately equal to the noise from the LNAs following the antenna ports. If this is the case \( \bar{v}_R \) and \( \bar{i}_R \) for each amplifier can be found using the noise figure, \( T_{min} \), and other parameters specified by the manufacturers.

Other correlation matrices can be defined for specific applications. For dish antennas it is helpful to define a spillover (\( R_{sp} \)) and sky (\( R_{sky} \)) noise correlation matrices that come from the portion of the antenna pattern that receives ground noise and sky noise. Using these two matrices, the external noise can be express as \( R_{ext} = R_{sp} + R_{sky} \).

### 2.3.3 Antenna Parameters Defined with Signal Model

Antenna parameters and figures of merit can be redefined using the signal model. The following equations show the signal model definitions using the weight vector \( w \) and correlation matrices [26, 27].

*Radiation Efficiency* (2.8)

\[ \eta_{rad} = \frac{w^HR_{iso}w}{w^HR_w} \] (2.38)

*Aperture Efficiency* (2.14)

\[ \eta_{ap} = \frac{k_BT_{iso}B}{A_{phy}S_{sig}} \frac{w^HR_w}{w^HR_{iso}w} \] (2.39)
Spillover Efficiency (2.15)
\[ \eta_{sp} = 1 - \frac{T_{iso}}{T_{ground}} \frac{w^H R_{sp} w}{w^H R_{iso} w}. \] (2.40)

Signal to Noise Ratio (2.12)
\[ \text{SNR} = \frac{w^H R_s w}{w^H R_n w}. \] (2.41)

System Noise Temperature (2.13)
\[ T_{sys} = T_{iso} \frac{w^H R_s w}{w^H R_n w}. \] (2.42)

Receiver Noise Temperature
\[ T_{rec} = T_{iso} \frac{w^H R_{rec} w}{w^H R_n w}. \] (2.43)

Spillover Noise Temperature
\[ T_{sp} = T_{iso} \frac{w^H R_{sp} w}{w^H R_n w}. \] (2.44)

Sky Noise Temperature
\[ T_{sky} = T_{iso} \frac{w^H R_{sky} w}{w^H R_n w}. \] (2.45)

2.3.4 Adaptive Beamforming

As mentioned earlier, an array has the advantage of being able to adapt to the communication environment and maximize the performance of the link because the weights are controllable. The beam can be steered while maximizing gain or SNR and minimizing interfering sources by finding the optimal weight vector. Even the antenna efficiencies can be maximized [28].

For satellite communication the most important item to maximize is SNR. The max-SNR beamformer is defined by
\[ w_{snr} = \arg \max_w \frac{w^H R_s w}{w^H R_n w}. \] (2.46)

Because (2.41) is a ratio of quadratic forms, this maximization leads to a generalized eigenvalue problem
\[ R_s w = \lambda_{max} R_n w. \] (2.47)
If $R_S$ is a rank one matrix (which is true for a satellite source because it is approximated as a plane wave at the receiver) than the max-SNR solution is [21]

$$w_{snr} = R_n^{-1}v_s. \quad (2.48)$$

### 2.4 Dish Geometry

The most common shape for a dish antenna is a paraboloid. A paraboloid is a parabola of revolution. This shape is ideal for dish antennas because parabolas have a focusing property; all rays parallel to the axis of symmetry reflect to a focal point or all rays from the focal point to the parabola reflect parallel to the axis of symmetry (see Figure 2.1). For this reason, and the effective size, dish antennas have high gain, being able to focus incoming energy and transmit highly directional waves.

![Figure 2.1: Parabolas have a focusing property. Rays parallel to axis of symmetry or focal axis reflect to a signal focal point.](image)

### 2.4.1 Symmetric Dish

Symmetric dishes are full paraboloids and have the feed at the center of dish on the focal point. The feed points toward the vertex of the paraboloid. These dishes are fully defined by two parameters: the focal length ($f$), which is the distance from the focal point to the vertex of the dish, and the diameter ($D$), which is the distance from rim to rim crossing.
the axis of symmetry. The geometry is defined by

\[ z = \frac{(x^2 + y^2)}{4f} - f \quad (2.49) \]

where

\[ x = \rho \cos \phi \quad y = \rho \sin \phi, \]
\[ 0 \leq \rho \leq D \quad 0 \leq \phi \leq 2\pi. \quad (2.50) \]

The way a feed illuminates a dish is related to the angular pattern of the feed and the opening angle of the dish. The opening angle of the dish is the angle from the axis of symmetry to the dish rim as seen from the focal point. The ideal feed for a dish would fully illuminate the surface of the dish and have no illumination beyond the dish rim. This would result in \( \eta_{ap} \) and \( \eta_{sp} \) being 100%. Because there is no feed that has an abrupt drop at the opening angle, feed patterns are designed to have peak gain within the opening angle, a 10dB falloff at dish rim, and keep side-lobes well below the 10dB falloff point.

The opening angle of a symmetric dish is related to the ratio of \( f \) and \( D \) \((f/D)\) by

\[ \theta^* = \tan^{-1} \left| \frac{1}{2 \frac{f}{D} - \frac{1}{16}} \right|. \quad (2.51) \]

The full illumination angle is \( 2\theta^* \) or \( \pm \theta^* \) when looking at the feed pattern. Feed patterns are defined by the \( f/D \). The larger the \( f/D \), the narrower the pattern from the feed must be.

### 2.4.2 Offset Dish

In SatCom, symmetric dishes are often used for transmitting and receiving at broadcast stations, but these dishes are too large for end users. When the dish size is minimized, the achievable SNR decreases and any signal blockage, even from the feed, could ruin the link. Offset dishes are sub-portions of a larger parent symmetric dish. The sub-portion is selected such that the feed no longer blocks the incoming signal.

Figure 2.2 shows how an offset dish relates to the parent dish. The opening angle of the feed forms a cone, and where that cone intersects with the parent dish, forms the dish
cut out. If the center axis of the cone is the same as the axis of the parent dish, the resulting dish cut will be circular in shape (symmetric dish). Now if the cone is rotated by some angle \( \theta_0 \), where the cone intersects with the parent dish, it will form an elliptical shaped dish. The feed has the same opening angle and no longer blocks the incoming wave. An interesting result of designing an offset dish this way is that, no matter how the cone is rotated, the projection of the dish onto the xy-plane will be circular [29, 30].

![Offset Dish on Parent Dish](image1.png)

![Top](image2.png)

![Side](image3.png)

![Front](image4.png)

**Figure 2.2:** Creating an offset dish by rotating a cone and cutting out its intersection with the parent dish. Center cone (red) has an opening angle \( \theta^* \) and is rotated 0 degrees. Offset cone (green) has the same opening angle but is rotated by \( \theta_0 \). The cone axis is marked in yellow.

While an offset dish can be defined by \( f \), \( \theta_0 \), and \( \theta^* \), most commercial dishes do not provide those parameters. This makes generating a model very difficult. The following
reviews how to generate the geometry of an offset dish given parameters provided with the dish \([29, 30, 31]\). Figure 2.3 shows a 2D cut of an offset dish to help with the steps below.

- The required parameters are \(f\), the long axis diameter \((D_L)\), and the short axis diameter \((D_S)\). If \(D_L\) and \(D_S\) are not provided, they can easily be measured. \(f\) is not always provided, but most dishes will specify \(f/D\). It is important to note that the given \(f/D\) for an offset dish is not the same as \(f/D\) for a symmetric dish. The commercial industry defines offset \(f/D\) as the ratio of \(f\) and \(D_S\). If neither \(f\) nor \(f/D\) are known then \([31]\) shows how to find \(f\) using the height of the deepest point in the dish.

- The projection of the offset dish onto the xy-plane is a circle. In order to define the offset dish, the center and radius of that circle must be found. The dish rim along the axis of \(D_L\) projected onto the xy-plane has a length of \(D_S\). The radius of the circle is simply \(D_S/2\).

- The center point of the circular projection is define by the point \(P(x_0, y_0)\). Let \(y_0 = 0\), to constrain the offset dish to be symmetric about the y-axis. Using the gradient of the parent dish at \(x_0\) and the angle \(\theta_{\text{off}}\), \(x_0\) can be found.

\(\theta_{\text{off}}\) is the angle between the apparent look direction and the actual look direction of the dish (see figure 2.3). By geometry, this angle is the same as the angle between the long axis of the dish rim and its projection on the xy-plane. This results in the following

\[
\cos \theta_{\text{off}} = \frac{D_S}{D_L}.
\]  

(2.52)

The slope of the long axis relative to the xy-plane is \(\tan \theta_{\text{off}}\).

The gradient of the parent dish with respect to \(x\) is

\[
\frac{\partial z}{\partial x} = \frac{\partial}{\partial x} \left( \frac{(x^2 + y^2)}{4f} - f \right) = \frac{x}{2f}.
\]  

(2.53)
With this information, $x_0$ can be solved as follows

\[
\frac{dz}{dx} = \tan \theta_{off} \quad \text{and} \quad \frac{dz}{dx} = \frac{x}{2f}.
\]

\[
\tan \theta_{off} = \frac{x_0}{2f},
\]

\[
x_0 = 2f \tan \theta_{off}.
\]

(2.54)

This works because at the point $P(x_0, y_0)$, the dish rim and the gradient are parallel.

- The geometry of the offset dish is found evaluating equation (2.49), where $x$ and $y$ are defined by equation (2.50), but the $\rho$ bound is changed to $0 \leq \rho \leq D_S$. Also, $x$ and $y$ are shifted by adding $x_0$ and $y_0$ respectively.

- $\theta^*$ and $\theta_0$ are solved using the law of cosines with triangles defined by the parent dish focal point, the parent dish vertex, and points at the top ($P_{TOP}$) and bottom ($P_{BOT}$) of the offset dish. By reference the focal point is $F(0, 0, 0)$ and the vertex is $V(0, 0, -f)$. $P_{TOP}$ and $P_{BOT}$ are defined as follows,

\[
P_{TOP} \left( x_0 + \frac{D_S}{2}, y_0, \frac{(x_0 + \frac{D_s}{2})^2 + y_0^2}{4f} - f \right),
\]

\[
P_{BOT} \left( x_0 - \frac{D_S}{2}, y_0, \frac{(x_0 - \frac{D_s}{2})^2 + y_0^2}{4f} - f \right).
\]

(2.55)

Applying the law of cosines $\theta^*$ is defined as

\[
\theta^* = \frac{1}{2} \arccos \left( \frac{\|P_{TOP}\|^2 + \|P_{BOT}\|^2 - D_L^2}{2\|P_{TOP}\|\|P_{BOT}\|} \right)
\]

(2.56)

and $\theta_0$ is defined as

\[
\theta_0 = \arccos \left( \frac{\|P_{TOP}\|^2 + f^2 - \|P_{TOP} - V\|^2}{2\|P_{TOP}\|f} \right).
\]

(2.57)

- Other parameters that are helpful for analyzing an offset dish are the diameter of the parent dish ($D_{\text{parent}}$) and effective $f/D$ ($f/D_{\text{eff}}$). $D_{\text{parent}}$ is equal to $D_S + 2x_0$. $f/D_{\text{eff}}$
is found by solving for \( f/D \) in equation (2.51). \( f/D_{\text{eff}} \) is a convenient parameter to analyze an offset dish using an equivalent symmetric dish, which simplifies feed design because the feed reference plane does not need to be rotated by \( \theta_0 \).

**Figure 2.3:** Geometry of an offset dish.
Chapter 3

Planar Feed Antenna Measurements

Commercial SatCom dishes are small in size because they are designed to be mounted on residential homes and not be inconvenient for the customer. The small size reduces the amount of signal the dish is able to gather. The reduced signal means that the feed must perform very well to keep sufficient SNR for decoding.

Planar antennas are smaller than horn antennas. This makes them capable of going into a feed array without making the array so large that it blocks an offset reflector or blocks a larger area than a feedhorn on a symmetric reflector. They are also capable of being built on the same board as the low-noise block down-converter (LNB). Planar feeds can be designed to fit most dish $f/D$s. Ideally this would make them cheaper to build and more versatile. They weigh less, occupy a smaller area, and take up significantly less volume than commonly used feedhorns.

Traditionally, planar antennas do not perform well enough to be used for SatCom. Most are built on a dielectric substrate and rough copper that causes more losses in the antenna as frequency increases. However, if they can demonstrate reasonable performance compared to a feedhorn, their additional benefits would make them a feasible replacement for common feedhorns. This chapter reviews the design requirements to compete with a feedhorn and some examples of well-engineered planar antennas that have the potential to outperform a feed horn. In order to test these antennas, test procedures and a dish mount had to be created.

3.1 Test Procedures and Set Up for Simulation and Measurement

The critical figures of merit for a reflector feed are spillover ($\eta_{sp}$), aperture ($\eta_{ap}$), and radiation ($\eta_{rad}$) efficiencies. Since these figures are hard to measure, it is often more
convenient to measure $G/T$ or SNR in a receive system, and gain and sidelobes in a transmit system. Since this work focuses on receivers, the measured figure of merit is SNR. The other figures of merit were simulated, with the exception of radiation efficiency on some antennas which the National Institute of Standards and Technology (NIST) measured for the research group.

3.1.1 Simulation

The efficiencies were calculated using a 3D FDTD solver [32] and a physical optics reflector modeling code developed by the BYU Radio Astronomy group. Radiation efficiency was calculated by the FDTD solver. The other efficiencies were calculated by extracting the 3D electrical fields from the FDTD solver and importing them in the reflector modeling code.

The modeling code generates a geometric model of the dish and the feed location. The feed’s electric field is projected onto the reflector and the surface current is calculated using physical optics. This current is then used in the electric far field integral from equations (2.1) and (2.3). The modeling code also analyzes the feed without the reflector to see how much signal is not reflected. The reflected field or secondary field and the field that misses the reflector are used to calculate spillover and aperture efficiencies.

3.1.2 Test Mount and SNR Measurement

The test planar antennas mount differently than feedhorns, so to help make the pointing process the same between the horn and the planar antennas a new mount was created (figure 3.1). The mount was made from a camera tripod which allowed telescoping (for y positioning), pitch, and yaw. The antennas were mounted on a wood base that slides toward or away from the dish (z direction). Figure 3.1(a) shows the test horn that is bolted onto the LNB. Figure 3.1(b) shows the test set up for the planar antennas. This was mounted to the tripod using the same wood base as the test horn. The horn was removed and a fixture mounted the planar antennas centered on the base pointing at the dish.

Once the feeds were mounted, they needed to be pointed. Initial pointing was done by positioning the feed in a similar location as to where a commercial LNBF would be positioned on the dish arm. Then fine adjustments in height (y), pitch, yaw, and focus (z) were made.
This order turned out to be very important to result in the best pointing. Lastly, the skew of the feed had to be adjusted to get the polarization aligned. All of the adjustments were made while monitoring the signal quality on the receiver. When the signal quality peaked, the feed was maximally aligned and pointed.

SNR measurements were taken using a professional satellite meter/receiver. This meter decodes the signal and calculates a bit error rate (BER). The meter calculates SNR using the signal modulation scheme and the BER.

### 3.1.3 Test Procedures

As mentioned earlier, planar antennas have not been known to perform well enough for SatCom. In order to fully understand whether planar antennas could replace feedhorns, test procedures were created. These procedures not only compare the key figures of merit, but they look at them over frequency and feed focus. Frequency response is important because many planar antennas do not have wide bandwidths. Focus was investigated because planar feeds can be harder to point correctly (section 3.3) and their robustness to pointing errors
has yet to be characterized, and the response as a function of focus can provide insight to the feed illumination.

In order to simulate the feeds over focus and frequency, the modeling code was modified to include sweeps. Changing the focus required changing where the reflector modeling code positioned the feed fields based on a z parameter. The frequency sweeps required extracting fields simulated at different frequencies and then running the reflector code for each frequency.

Measured focus sweeps were performed by sliding the wood feed mount in and out from the dish while measuring the distance moved from the center focus point and recording the SNR. The frequency response of the feed was performed by measuring the SNR at different transponders across the 11.7-12.2 K\textsubscript{u} band.

### 3.2 Antenna Designs

This section provides the model and tests of a feedhorn, and a sample of the planar antennas designed by the BYU SatCom group. Antennas designed by other group members are noted in the model figures. The main contribution of the section is introducing these antennas and presenting the results of simulation and testing.

The measured results for antennas are shown with dashed lines. The simulated results are show with solid lines. The tests looked at the antennas’ performance vs. frequency and performance vs. focus (− is away from dish, + is toward the dish).

The measured SNR is different from the simulated SNR for a number of factors: simulated SNR only accounts for noise through the LNA, does not factor in connector losses, assumes uniform EIRP for all transponders, and does not factor in atmospheric and weather related losses. The measured SNR is calculated from Bit Error Rate (BER) and therefore take all environment, system, and transponder EIRP effects into account.

Towards the end of this chapter is figure 3.15 which shows a comparison plot of all the measured antennas based on SNR measurements across focus and frequency. Of note is that the planar antennas have a slower SNR decay as the feed moves closer to the dish. This may suggest that these antennas have too much spillover; therefore, as they move towards
the dish, SNR is degraded due to defocusing, but spillover reduces and buffers the degraded SNR.

**Horn**

Horn antennas have been used for SatCom for over 40 years. They have very high radiation efficiencies and can be connected to very low loss waveguide components. It is also fairly straightforward to design the horn flare to achieve the correct pattern to maximize spillover and aperture efficiencies. Figure 3.2 show a feedhorn designed for an offset dish with an $f/D$ of 0.6. Figure 3.3 shows the performance of the feedhorn and the bar for all other antenna designs.

![Figure 3.2: Traditional feedhorn for offset dishes.](image)

It is important to note that surpassing any of the horn efficiencies is a significant achievement but the true test for commercial applications is whether the SNR can be matched or surpassed. While horns are cheap to cast they do require additional assembly steps and are bulky. This makes them more expensive than just an enclosed PCB and requires strong mounting hardware for the reflector. Therefore, if a planar
PCB based antenna can achieve reasonable performance, it would make a feasible replacement, reducing additional assembly steps, size, and weight.
2x2 Square Passive Array

The square patch is one of the simplest planar elements to design, but substrate and copper roughness cause loss making it difficult to get the radiation efficiency high enough for SatCom. They also, until recently, have not been specifically designed to feed dishes. Special consideration must go into the patch design to mitigate losses and improve efficiencies.

Figure 3.4 shows a square patch array. This design uses a low loss substrate and phase offsetting to help improve isolation. At least a 2x2 array is required to obtain the beam pattern needed to illuminate the test dish with an $f/D$ equal to 0.6. This design is beneficial because it has dual polarization and is on a single substrate core which keeps costs low. The improved isolation also prevents additional loss caused by the signal leaking into another port [8].

![2x2 Square Passive Array](image)

**Figure 3.4:** 2x2 square passive array designed by Zhenchoa Yang, PhD Candidate.

Figure 3.5 shows the results for this antenna. This antenna performed well in simulation and test; however, radiation efficiency is lower because of substrate and feed network losses, and the percent bandwidth is much lower for a patch antenna than a horn. For the band of interest (11.7GHz to 12.2GHz) the simulated SNR is about 1dB lower and
<0.5dB for the measured SNR. Some of the extra loss in the measured results is due to connector loss (0.2-0.3dB) because the designed antenna requires additional adapters to connect to the LNB.

Figure 3.5: Performance of a 2x2 array.
Hex Passive Array

The hex array, figure 3.6, was designed to address some of the issues with the 2x2 array. Adding more elements increased the degrees of freedom allowing more flexibility in the beam pattern. The new configuration has better radiation efficiency. As can be seen in the simulation results of figure 3.7, the aperture efficiency is almost 10% higher than the feedhorn, the spillover and radiation efficiencies are 5% higher than the 2x2 array, and the bandwidth is wider. The simulated SNR is only slightly below that of the feedhorn.

Figure 3.6: Hex passive array designed by Zhenchoa Yang, PhD Candidate.

Beyond the additional degrees of freedom, this design uses two substrate cores. One core is dedicated to the antenna and the other is for the network. This reduces losses by selecting the best material for each function. Radiation efficiency and bandwidth are improved if the antenna is on a thicker core. On a thick core, the network is too large, so thinner is better for feeding [9].

The disadvantages to this design are that it uses multiple substrate cores, which costs significantly more to fabricate, and it is only single polarization. An attempt was made to decrease fabrication costs by breaking the antenna layers onto single core designs.
(a) Hex array efficiencies as a function of focus.

(b) Hex array efficiencies as a function of frequency.

(c) Hex array SNR as a function of focus.

(d) Hex array SNR as a function of frequency.

Figure 3.7: Performance of a hex array.

and then screwing them together, but it did not work well. This is why the measured results are poor compared to the horn. However, this antenna, as seen in simulation, has the greatest potential of replacing the horn, but it will require further research.
### 3x3 Square Passive Array

Figure 3.8 shows a 3x3 patch array. A 3x3 array is advantageous because it can be tuned to feed different $f/D$ dishes. The disadvantage is that it requires a larger feed network, which increases losses, and may even require multiple cores for dual polarization. This particular design tried to reduce the larger network by using series feed, which could possibly achieve dual polarization without going to multiple cores as well.

![3x3 Square Passive Array](image)

**Figure 3.8:** 3x3 square passive array antenna.

The design was brought about by the idea that radiation efficiency could be increased by spreading the current out as fast as possible over a larger surface area [9]. To do this, the antenna port feeds directly to the center element and is then distributed to thin traces instead of going to the thin traces first. The network that connect all the elements help to keep the same modes excited on all the elements. Without all the traces the corner elements tend to have circular modes.

This antenna was fabricated in its infancy and was not fully optimized. There are a lot of phase and matching issues that need to be ironed out as can be seen by the efficiencies and bandwidth in figure 3.9. However, signal was captured and it shows that the concept can work.
DRA Passive Array (Rev1 and Rev2)

Dielectric Resonator Antennas (DRA) are quasi-planar antennas that have a small dielectric block that can be bonded to a copper feed and PCB. They are known for...
being wide band. The also can be made very small because they are scaled by \(1/\sqrt{\varepsilon_r}\) [24].

Figures 3.10 and 3.12 show two versions of a DRA array [33]. Each version used a different dielectric block and was optimized for the material. Figures 3.11 and 3.13 show the results.

![Figure 3.10: DRA passive array (Rev1) designed by Binh Tran.](image)

They both perform well, but further research is required to make them better. The bandwidth of these antennas is the greatest feature, which is similar to that of the feedhorn. This would make them good options for multi-band feeds where the real estate does not allow for multiple apertures.

Note that figure 3.11(b) shows measured radiation efficiency; only DRA Rev02 was measured and the efficiency is on this plot for reference. Also, these antennas were not tested on a dish for this work.

0.3 \(f/D\) Patch Antenna

Horns are difficult to design for low \(f/D\) values because their beamwidths are too narrow. In many low \(f/D\) dishes, sub-reflectors with higher \(f/D\)s are used to aid the narrow feedhorn. Planar antennas can be designed to illuminate almost all \(f/D\)s. The patch antenna shown in figure 3.14 is a concept design used to feed a dish with an \(f/D\)
equal to 0.3 without using a sub-reflector. It was designed by request from the project sponsor.
The antenna was designed using the approximate field pattern that would be required to illuminate a low $f/D$ dish. A single patch’s beamwidth is too wide for a dish with an $f/D$ of 0.3, so passive elements or a conductive wall need to be introduced in order to increase the gain slightly. The can in the figure is smaller than a horn.

Being a concept design, the antenna was never fabricated and no measurements were taken. While there are no plots for this antenna it can be assumed to be close to the 2x2 patch array with slightly higher radiation efficiency because no feed network is required and the SNR will differ depending on the model dish size.

### 3.3 Other Planar Antenna Challenges

As mentioned earlier planar antennas were harder to focus than a feedhorn. Most feedhorns have a waveguide structure built with the antenna that is used for mounting, and therefore, standard antenna mounts sit several centimeters behind the dish focus and antenna phase center. The phase center of a planar antenna is located differently than a horn relative to the dish, so antenna mounts must be able to move in and out from the dish ($z$ dimension). Dish feed arms are fairly well positioned in the $x$ and $y$ dimensions and do not require adjusting. Horns usually mount along the same axis as the dish focus, so they roll, pitch, and yaw around that axis. They are also long enough to easily make fine adjustments. Planar antennas are short and little rotations in pitch and yaw greatly change
the pointing direction. Roll is also difficult because the connectors on the antenna are not centered with the phase center, so rolling does not just adjust the polarization alignment,
Figure 3.14: Patch antenna designed to feed a dish with $f/D$ equal to 0.3.

but also the x-y position. From a visual pointing perspective, the horn appears more like a barrel and is easier to aim than a planar antenna that looks more like a plate.

The test mount did not fully solve the roll issue, which may also account for some of the performance differences due to polarization mismatch and lateral movement. The horn polarization was adjusted be spinning the horn and its center axis. Because of connector locations, the planar antennas could never be rolled on their center axis.

Figure 3.1(b) shows the extra connectors required to test the antennas. The horn connects directly to the LNB in a very low loss transition. The other antennas have SMA connectors that connect to an SMA to N-type adapter, which then connects to a N-type to WR-75 waveguide adapter. The connector chain adds loss (about 0.2-0.3dB) and degrades performance.
(a) Measured SNR as a function of focus

(b) Measured SNR as a function of frequency

Figure 3.15: Comparison of all measured antennas.
Chapter 4

Designing an Electronically Steered Array Feed

Fixed beam communication systems have their advantages, but they are limited in capability. High gain antennas, such as those required for SatCom, must be carefully pointed in order to minimize loss. As frequency increases, the difficulty to accurately point increases. In order to implement tracking, bulky and expensive mechanical steering and tracking equipment must be used. Communicating with different targets requires separate antenna systems for each target. In the case of SatCom, this not only requires multiple feeds but also a new reflector design. The limitations of fixed beam communication motivate the need to develop a more robust solution for a communication system.

Aperture array antennas offer the ability to electronically steer, track, and form multiple beams. These arrays consist of multiple elements spaced across an area. The number of elements in the array influences the gain of the antenna. In order to achieve the gain required for SatCom, these arrays have hundreds of elements. In order to achieve steering, each element or small groups of elements must have individual control of phase and gain that gets applied to the array. All the required electronics make aperture arrays expensive to implement. An array feed uses the dish reflector for the high gain and requires less electronics to achieve steering. This makes an electronically steered array feed (ESAF) an ideal solution to overcome fixed beam limitations while keeping costs low.

This chapter outlines the design of a low-cost ESAF. There are two designs submitted it this work: a 2x4 ESAF and a 4x4 ESAF. Section 4.1 reviews how an ESAF works and the design requirements. Section 4.2 discusses the antenna elements and the layout of the elements. Sections 4.3 and 4.4 cover the beamformer. Section 4.3 also introduces a study of requirements for ESAF beam weights. This chapter finishes by discussing the hardware and software used to control the ESAF.
4.1 ESAF Background and Requirements

4.1.1 Background

Dish reflectors are a type of aperture antenna. One of the properties of an aperture antenna is that, electromagnetically, they perform an operation similar to a Fourier transform. The transformation occurs between the voltage/current domain and the radiation far-field domain. If an aperture antenna is excited uniformly, the current is rect-like across the aperture; meaning, the magnitude is greater than zero within the effective area of the aperture (the area that can receive energy and most often is less than or equal to the physical area) and zero elsewhere. This excitation will cause the aperture to radiate the energy, minus losses, in a sinc-like pattern in the far field. If the excitation current has a linear phase shift across the aperture, the radiated field is shifted in angle. This means if a parabolic dish is uniformly illuminated by a plain wave, the field at the dish focus will have an annular sinc-like distribution. If the wave comes in off boresight (dish pointing angle equal to 0°), a linear phase is introduced over the dish aperture and the field is pointed off the dish focus [30, 10].

In an aperture array, introducing a linear phase across the array causes the beam to steer. Adjusting the amplitudes of the elements changes the field pattern, but maintains the steering direction. Alone, an array feed follows the same principles, but when feeding a reflector the fields undergo a transformation. The primary beam (radiated fields from the feed) of an array feed reflects to form the secondary beam (radiated fields from the reflector). The reflector causes the roles of phase and gain in the feed to switch.

To steer the secondary beam a linear phase shift must be introduced on the reflector aperture. This is done by spatially changing the primary beam away from the focus of the dish. In other words, the pointing direction of the feed is not changed, but rather the beam shape is changed so that the primary main lobe is not at the feed center; this is done by adjusting the gain. Likewise, the phase of the feed helps shape the secondary beam. Figure 4.1 helps explain this principle.

Viewed as a transmitter, the goal of an ESAF is to steer the secondary beam in a given direction while fully illuminating the reflector and minimizing the spillover (minimizing
Figure 4.1: Incoming waves will reflect off the dish to different locations on the focal plane and will also be distorted. (a) shows possible reasons why a signal may be off boresight. (b) shows how the reflected beams are shifted on the focal plane. The red represents the feed’s field distribution.

sidelobes). A fixed feed cannot steer the secondary beam and has a fix illumination. If it is moved to different positions it can steer the beam slightly, but the illumination will not be optimal, gain will drop and sidelobes will increase. ESAFs can steer and optimize the illumination pattern.

The central idea of an ESAF, viewed as receiver, is to change the feed’s field pattern to match the field distribution projected onto the focal plane by a reflected incident wave [10]. As can be seen by the red pattern in figure 4.1(b) attempting to match the black pattern on the focal plane. ESAFs gain advantage over fixed beam feeds due to the ability of adjusting and matching the field distribution on the focal plane. Figures 4.2 and 4.3 demonstrate the ability of ESAF to overcome the limitation of a fixed feedhorn.

The feedhorn is designed to capture the majority of the energy reflected by a dish when pointed at boresight. With this alignment, the phase center of the horn and the focal point of the reflector align. As the signal moves off boresight, the field center moves off the dish focus, distorts [10], and no longer aligns with the feedhorn phase center. Even if the feedhorn were to move and align its phase center with the field center, it still cannot compensate for the distortions and captured energy decreases.

An ESAF has the ability to adjust its phase center to align with the field center as shown in figure 4.3. It can overcome distortion due to steering by changing its effective
Figure 4.2: The sinc-like pattern of a reflected wave onto the focal plane and captured by a horn feed. As the target moves, the reflected field moves off focus and distorts. The black ring represents the focal point (phase center) of the horn.

shape. It even has the ability to overcome other distortions due to mechanical tolerances in the reflector [34]. And sometimes, even at boresight, feeds do not have the ideal field distribution, but ESAFs can adapt and change their field distribution. Figure 4.4 compares the normalized field patterns of a feedhorn and ESAF using weights optimized for maximum SNR. As shown the ESAF creates a pattern optimized for SNR with higher gain.

Figure 4.3: The sinc-like pattern of a reflected wave onto the focal plane and captured by an ESAF. As the target moves, the reflected field moves off focus and distorts. The black ring represents the focal point (phase center) of the ESAF.
Figure 4.4: Simulated secondary field pattern cuts of a fixed feedhorn and an ESAF optimized for maximum SNR on a 90cm dish with an $f/D$ of 0.6.

4.1.2 Requirements

As mentioned before, ESAFs are already being used with very expensive hardware [35, 10, 34]. Thus far the applications have been limited to radio astronomy and high end satellite systems. This research focuses on the possibility and demonstration of ESAFs for commercial applications.

For commercial satellite communications, low-cost and high performance are the driving requirements. Arrays can be designed to perform exceptionally well, but cost goes up dramatically with every performance upgrade and new feature. If the array is incredibly
low-cost, then many of the unique features of an array are lost. The challenge is to pack as many features as possible while keeping it cheap enough that the industry wants it.

Below are the high level requirements for implementing a commercial ESAF.

- Low-cost
- Performance comparable to commercial feedhorns
- Minimize additional hardware and additionally must be independent of current SatCom receivers.
- Additional features beyond fixed feeds

While portions of these requirements are addressed in this work, the prototypes developed here, as will be seen later, are not optimized to meet the full requirements. However, these designs demonstrate a much lower cost ESAF implementation and a path forward to meet and surpass the requirements. This is a feasibility demonstration and future research will be required to meet the full requirements.

4.2 Array Structure and Element Design

Two arrays were developed as seen in figure 4.5. For ease of design and simulation both are placed in a rectangular grid. The elements are single polarization slot patches in two configurations, 2x4 and 4x4. A 2x2 sub-array of the elements used in these arrays has performance similar to figure 3.5; however, the radiation efficiency is lower because the substrate used has higher loss.

The 2x4 array (figure 4.5(a)) was built on a signal substrate core with the electronics placed on the same side as the elements. It has two passively combined elements per RF chain using inset feeding. Due to the passively combined elements, this array really is only a 1x4 active array allowing steering in one dimension.

The passively combined elements are to achieve dish illumination in that dimension. As mentioned in section 3.2, at least a 2x2 array of elements is required to illuminate a dish with an $f/D$ of 0.6.
The 4x4 array (figure 4.5(b)) has no passively combined elements and each element feeds an RF chain using a via. The 4x4 was on two substrate cores with the electronics placed on the opposite side as the elements. The component layer and the element layer are separated by ground planes. This array allows steering in two dimensions.

The multi-core design was selected to keep the board small and get the LNAs as close to the elements as possible. It also has the advantage of allowing a thicker antenna core to improve performance and bandwidth. It does, however, increase the cost of the ESAF.

![Figure 4.5: The fabricated element arrays used in the ESAFs. (a) The array structure that illuminates a dish with an $f/D$ equal to 0.6 and has four active channels. (b) The array structure for 16 active channels, designed to have the same steering range as (a) but in two dimensions.](image)

In both designs, only 4 element and RF chains were chosen per dimension. This was done because it allows some steering without steering into adjacent satellites. Avoiding other satellites greatly reduces the hardware requirements and need to interface with available receivers because the system does not have to recognize the target to track and point.
4.3 Beam Weight Optimization

As discussed in chapter 2, the array weights (magnitude and phase of a signal) control beam shape and steering. This is done by applying different complex signals to different elements in the array. Complete control of the array is accomplished by being able to achieve any magnitude and phase for each element. The realization of this beamformer would require a digital system or wide range variable gain amplifiers (VGA), phase shifters, and receivers located behind every element. Unfortunately, today’s technology, these options are very expensive and too large to exist at every element. Thus, methods must be developed to simplify the electronics while still maintaining some features of an active array. The remainder of this section will talk about the methods for simplifying electronics and finding optimal beam weights with the simplifications applied.

4.3.1 Modeling the Array Elements

Using a 3D FDTD solver [32] the arrays in figure 4.5 were simulated with a port placed at each element chain. The 2x4 had four ports and the 4x4 had 16 ports. By turning each port on one at a time and running a simulation for only a single port, leaving the rest as loads, fields and port impedance were extracted. The impedance is required because the array models developed in chapter 2 and in [21] require the array to be simulated with one excited element and the rest left open loaded. The far fields contain information about how the active element radiates and how each other element in the array interacts with the one element. The fields are referenced to a simulated phase center, which may not be the same point for all elements. In order for array models to work correctly, all fields must be referenced to the same point.

As mentioned above, the models require an open port reference and this is accomplished by transforming the port impedances from the simulated impedance to open impedance using network theory and scaling the fields accordingly. Once the fields are properly prepared, they are individually placed in the PO reflector model port by port. The element fields are positioned around the dish focus according to their relative position in the array reference by the phase center. In other words, the array center would be located at the dish focus and every element field would be translated according the dimensions from
the array center. The secondary fields for each element are obtained after running the PO model.

4.3.2 Applying the Array Signal Model

Even though the elements were reflected off a dish, there is a secondary field for each element and can therefore be treated as if it were a normal antenna array. These fields can be placed in a column vector and defined with a polarization and direction as per equation (2.23). $E_p$ is then used to calculate $v_{oc}$ (2.22) assuming $E^{inc}$ is co-polarized and is calculated using the EIRP of a satellite. From $v_{oc}$, $v$ can be calculated using equation (2.24). $Q$ is calculated assuming each RF chain is the same for all elements and that the impedances are matched throughout the system, so the only things to account for are the RF chain gain and the voltage divider caused by the mutual impedance matrix ($Z_A$) and the system impedance ($Z_0$). Using these parameters, $Q$ becomes

$$Q = GZ_0I(Z_A + Z_0I)^{-1}. \quad (4.1)$$

$Z_A$ is extracted in a matrix from the simulated port impedances.

After $v$ is found, the fields and system components specifications are used to calculate the correlation matrices and other parameters listed in section 2.3.2. With this information, the antenna parameters from section 2.3.3 can be calculated and adaptive beamforming algorithms can be used.

4.3.3 Adaptive Beamforming and Weight Optimization

These ESAFs are used only as receivers for this work, so only max-SNR beamforming was used to optimize beam weights. The max-SNR beamformer solution is found in equation (2.48) assuming no restrictions on the weights. This solution sets the SNR ceiling for all other beam weight configurations.

The objective of this experiment is to maximize the SNR across the entire steering range of the array. This is done by changing the direction that $E^{inc}$ arrives at the dish and recalculating $v$ for each arrival angle across the steering range which is effectively $\pm 1.5$
beamwidths or ±3°. After ±3° the SNR drops too low for the signal to be decoded in real measurements. After all the vs are found, optimal weights are found using equation (2.48) or an optimization algorithm and applied to equation (2.41). Figures 4.6 and 4.7 show the results of max-SNR beamforming and SNR weight optimizations when restrictions on the available values of magnitude and phase values are implemented.

Max-SNR beamforming requires that there be an infinite number of values to select weights from. Electronic components have limited output ranges and to simplify electronics and bring down the cost, electronics often use discrete steps within their output range. The less steps available, the simpler and cheaper the electronics will be. So the discrete weights study investigates the ESAF’s response when available values are restricted. It also can help to pick the best values for a component to output.

The discrete weights were chosen by first allowing 4 gain/4 phase, 2 gain/2 phase, 4 gain, or 2 gain values to be used to select beam weights from. With number of values selected, the next step was to optimally pick values that created weights to maximize the average SNR between −2° and 2°. This required a double optimization loop. The outer loop optimized the allowed values and calculated the average SNR, and the inner loop optimized the weights for SNR at different arrival angles within the specified range. The loops result in the best values to maximize the average SNR and the SNR over the steerable range. This translates to building VGAs and/or phase shifters that need to only output specific values. These components could be implemented cheaply.

The results of this study are impressive. First and foremost, this study shows that by removing phase shifters from the beamformer, which are 5 to 6 times more expensive than the VGAs, the ESAF takes only a slight hit in SNR, 0.1dB on the 2x4 and 0.3dB on the 4x4 with only 4 discrete values. The reason phase does not play a critical role, as explained earlier in this chapter, is because the array is small and in an array feed, phase performs beam shaping which is not critical to beam steering. While not shown in the plots, adding more values minimizes the SNR differences between gain only and gain/phase beamforming, but even if infinite gains are available it will not perfectly match the max-SNR beamformer.

Another impressive result of this study is how few values are really required to maintain good SNR. For less than a 1dB SNR loss, only two gain values are required. This is
Figure 4.6: Max-SNR beamforming under different weight configurations using the 2x4 array in figure 4.5(a).

like turning amplifiers on and off in the array, which does not require any beam weighting components. Notice as the number of values decrease, saddles become more apparent. This is because the dish requires at least a 2x2 array of elements to illuminate the dish well. In one dimension these arrays only have four elements. So for the 2x4 array with only two gain values there are only three 2x2 sub-arrays where two chains will have high gain and the others will have low gain. The saddles occur when the signal peak falls directly onto one element chain requiring one chain to have high gain and the others to have low gain,
thus illuminating the dish with a 1x2 sub-array and very small contributions from the other elements. Note that adding some phase does mitigate the SNR loss more as the gain values decrease.

Other things to note from the figures are SNR difference between the 2x4 and 4x4, and some of the plots that should have worse SNR, surpassing plots that should have better SNR. The 4x4 achieves better SNR for the same reason that the hex array in chapter 3 performs better than the 2x2 array. The 4x4 allows each element to be weighted and therefore has

**Figure 4.7:** Max-SNR beamforming under different weight configurations using the 4x4 array in figure 4.5(b).
more degrees of freedom. While a 2x2 array illuminates the dish well, it is not the most optimized shape to illuminate the dish and the 4x4 array allows a better pattern shape to be created. The crossing of the plots is caused by the double loop optimization. Because the goal is to maximize the average SNR over a range of directions, values are selected that increase SNR at the steering edges to boost the average SNR, but that may lower SNR towards boresight. When fewer values are available, no values really increase edge SNR, so to boost average SNR, weights have to be selected that achieve higher SNR in certain directions. Another issue is that beam weights are selected relative to the other weights in the array (0 1 1 0 is the same as 2 3 3 2) so there are an infinite number of solutions to maximize the SNR and some weights do not change the SNR significantly. This means that the cost function has many minima and many of those do not stand out from their neighbors; therefore, optimizers struggle to converge on the global optimum.

### 4.4 Active Component Selection

In today’s satellite and high frequency component world, there are not many options in the way of beamforming hardware. There are commercially available phase shifters and VGAs in separate packages, but they are too large to fit within the element space of a patch antenna. On top of that, phase shifters are really only used in array applications, which are not widely used in low-cost SatCom terminals, so they are very expensive. Luckily, VGAs and variable attenuators are commonly used for signal conditioning, so low-cost options are available. They, or their surrounding circuitry, still occupy a lot of real estate. There are also systems for digital beamforming, but once again, this requires a receiver consisting of an LNA, filters, mixes, and ADC at each controllable element and then a bulky and expensive computer for signal processing. The advantage is that all beamforming options are available through software configuration, whereas with analog devices, the circuitry gets more complicated to realize interferer cancellation or multi-beam communication, for example.

The beamformer and components in it was a key portion in this research and meeting the ESAF functionality and low-cost requirements. As discussed previously, steering can still occur without phase shifters and not lose significant SNR. Also, simplifying the VGAs is possible and even removing them all together if it is okay to have dips in the SNR. However,
continuous VGAs with about 20dB of gain range are fairly cheap and therefore the added full range of steering was left in these ESAF. Figure 4.8 shows a block diagram for the 2x4 ESAF. Similar chains are found on the 4x4 feed. The signals are combined using a cooperate network.

![Block diagram for the 2x4 array](image)

**Figure 4.8:** Block diagram for the 2x4 array. The 4x4 is similar with 16 channels and no passively combined elements.

The LNAs are Avago AMMP-6220. They are internally matched to 50Ω and require no biasing; therefore, no matching is required and only a voltage line has to be run to the part. This greatly reduces the design time and complexity. They are about the same size as the array elements and their noise figure (NF) is high for SatCom at about 2.1dB. Most SatCom LNBFs have NF around 0.7dB. The added noise can be seen in figure 4.9. In figure 4.9(a) the ESAF is simulated with NF equal to 2.1dB and the horn is simulated with NF equal to 0.7dB. Figure 4.9(b) shows the same azimuth steering cuts if both LNAs had a 2.1dB NF. With a 2.1dB noise figure the receiver noise out weights the noise due to the ESAF having lower radiation efficiency. A better LNA would be a transistor based design with very low noise and miniaturized matching networks, DC blocks, and RF chokes so that they could fit within the element space.
Figure 4.9: SNR as a function of azimuth steering angle plots. (a) The antenna performances with LNAs similar to actual components used in testing. (b) The antenna performances if both antennas had the AMMP-6220 LNA.

The VGAs are Avago VMMK-3503. They require external biasing, but are matched to 50Ω. The package is very small, about the size of a small chip resistor. Two voltages are required, the control voltage \( V_c \) and the drain voltage. They are specified to have a 20dB range at 12GHz from -10dB \( (V_c = 0.65V) \) to 10dB \( (V_c = 1.8V) \). \( V_c \) can go down to 0V to increase the range, but the gain is not as well behaved with a \( V_c \) variation below 0.65. Figure 4.10 shows a plot of the VGA gain vs \( V_c \).

Figure 4.11 shows the finalized beamformer design with components. Figure 4.11(a) was the first iteration of the 2x4 array. While it could receive signal, the connector and cable loss before the LNAs and the LNA NF diminished the SNR too much for good testing. It did prove the concept. The second iteration, figure 4.11(b), was built with everything on one board. The LNAs are the white blocks. The VGAs are small, but they are the components surrounded by chip capacitors, resistors, and inductors. Figure 4.11(c) is the backside of the 4x4 array. The antenna vias down the component layer, then the signal hits the LNAs which are located as close to the feed vias as possible. The inner LNAs had to be rotated...
45° in order to keep the RF traces from intersecting with other traces. There was also not enough room to place the VGAs close the LNAs for the inner elements. For combining, all the RF chains had to be in-phase. The meander lines for the inner elements as well as the non-symmetric combiners at the top and bottom of the board create the necessary delays to get the signals in phase by the second combining stage. The trace lengths on the left and right combining stages also match the phase for those signals when they are combined with top and bottom signals.

The component layout of the 4x4 board raises some concerns with low cost ESAF design with current technologies.

- Figure 4.5(b) shows that board dimensions are much larger than the element array requires. The size was increased to allow the combining network to exist on as few layers are possible. By adding more cores to the stack-up, the x-y dimensions would decrease, but board fabrication costs would increase significantly.

- In order to minimize size, the combining cuts back to the center. This closes off any open paths for DC network or to add another polarization to the antenna. This design
Figure 4.11: The ESAF fabricated RF chains. (a) LNA and active components for the 2x4 array in a connectorized prototype. (b) LNA and active components for the 2x4 array. (c) LNA and active components for the 4x4 array.

requires a separate DC board that attaches to the header pins. Once again this could be solved by adding layers.

- The components are too large for a dual polarized antenna in any grid array larger than 2x2. There is not room to place separate combining networks along with double the components. It may be possible if the board grows and LNAs are not placed close the antennas; however, the larger the board, the greater the possible reflector blockage.
• The size of the components and real estate for the combining networks makes it difficult to make the array larger than 4x4, which would be necessary to increase the steering range. The current components occupy the same space the new elements would need for their components. The solution would be to grow the board and spread out components, but then transmission line loss and phasing become a serious problem.

A good solution for these problems, would be designing low cost components that are specialized for PCB based arrays. For example, a chip with integrated LNA, VGA, and phase shifter that in a MMIC package would occupy the same space as the current LNA used in these ESAFs.

4.5 Array Control System

All active arrays have a control system incorporated with the array. These systems are either built onto the array or separate units that cable to the array. For a commercial ESAF the control system would need to be integrated with the feed so as not to require extra equipment. For research, keeping system components separate is more practical so each portion can undergo iterations independently. Once everything is functioning, then integration can occur.

The array control system for these ESAFs has two portions, the hardware controller and the software. The hardware is shown in figure 4.12 and the software is shown in figure 4.14. The hardware controller consists of a micro controller (µController) and a DAC board. The software can run through a computer, which is more transparent to the user, or automated by the µController code.

The µController is incorporated into an Arduino board. The Arduino board, or any other µController development board, is convenient because the board is already built and the programming interface is easy to use. A program is developed on a computer in C/C++ and Arduino software translates the code and programs the memory and registers of the µController. The DAC board consists of six DAC chips, voltage regulators for DAC reference voltage, and some EEPROM memory chips (for features not yet developed). The µController serially programs each of the DAC chips using a word that contains address and output value information. There are 12 addressable DACs per chip and every DAC can have
Figure 4.12: The controller board which is composed of an Arduino or Sanguino board and a module board of DACs. (b) shows the block diagram of the module DAC board.

an 8 bit value or 256 different output voltages. The board is capable of controlling up to 72 VGAs and can be updated thousands of times a second. After the DACs are programmed, the output voltage cables out to the VGAs on the ESAF. Figure 4.13 shows the voltage output at each state or bit value (use figure 4.10 to translate to gain).

The software is capable of many different features, most of which will be mentioned in the next chapter. Here the focus is on controlling the array. The manual control section of the UI, figure 4.14(a), the user can select the state for each VGA in the array. Because DACs are used, the system does not have truly continuous gain control even though the VGAs are continuous, but the DACs allow 256 states which translates to gain changes of about 0.14dB. And as shown earlier in the chapter, ESAFs can get by with fewer gains than 256. To test this and because manually optimizing every VGA with 256 states takes a very long time, the user can select a number of states to use between 0 and 255. In other words, if the user selected 5 states, the available options would be 0, 64, 128, 192, and 255. Once a state is selected, the computer tells the μController through a custom serial command to set the appropriate DAC chip, channel, and voltage output. States can also read in from a file and run automatically by either the computer or the μController for features like acquisition and tracking.
Figure 4.13: The DAC output voltage as a function of state or bit value.
Figure 4.14: Screen shots of the (a) array control user interface and the (b) $\mu$Controller programmer and code.
Chapter 5

Testing the Electronically Steered Array Feed

Simulations tell us a lot about systems and their performances. It is, however, only a small part of proving a concept. As shown with the antennas in chapter 3, there are unseen and unmodeled effects in simulation that occur in reality. Many things are modeled that are not currently feasible to produce. The purpose of this chapter is to show the results of the design work done in chapter 4, state some of the prototyping difficulties, introduce the tracking feature, and explain the test setup. Section 5.1 reviews the test setup and procedures for the ESAF as well as showing the results of testing and simulation. Section 5.2 covers how to get the ESAF to track a satellite. Section 5.3 discusses the challenges that were encountered in manufacturing and testing.

5.1 Testing the Steering and Performance of the ESAF

All the testing, including the antennas in chapter 3, was performed on a roof mounted dish pointing at a live FTA satellite. The dish was attached to a motor that could sweep in azimuth, east to west. Originally, measurements were made using a spectrum analyzer, an FTA receiver, and TV. Later the measurement system was upgraded to a satellite meter that professional dish installers use. This device was faster, gave more information regarding performance, and performed a more accurate measure of SNR. The ESAF itself was fixed to the same mount described in chapter 3. Figure 5.1(a) shows the test setup (measurement system not shown) with the 2x4 ESAF mounted to the dish. Figure 5.1(b) show the fixture for the 4x4 ESAF and this would attach to the camera tripod mounted to the dish.

When performing any on-dish testing, the first step was to return the dish and motor back to boresight (0° azimuth). This was done using a commercial fixed LNBF and adjusting the motor until the signal was maximized. Then LNBF was removed and the test mount
put into place. Once all the fixtures and mounts were in place, it was time to adjust the feed pointing and focus. Initial pointing was done by just trying to get the ESAF to point at the dish similar to how the LNBF points at the dish. Next, using the UI (figure 4.14(a)), the gain was turned high on the center 2x2 sub-array of the ESAF and all other element gains low. While this was not necessarily the optimum beamweight for SNR, it allowed the center of the array to fall at the focus of the dish. Then fine adjustments in height (y), pitch, yaw, and focus (z) were made. This order turned out to be very important because, for example, pitch can adjust for poor pointing in y, much like the ESAF can steer the beam by hitting the dish off focus, but this does not lead to maximum SNR.

Once everything was pointed, using the UI the beam weights were adjusted until the maximum SNR was achieved. This became the boresight beam weights and the best SNR. From there, measurements could be taken similar to those in chapter 3. Using the motor,
the dish could be steered east or west and at different points new beam weights could be optimized and measurements taken.

Figure 5.2 shows a comparison plot of the 2x4 ESAF and the horn vs frequency. The SNR difference is primarily caused by the LNA NF, but other issues are discussed in section 5.3. Figure 5.3 shows a side-by-side of the 2-dimensional steering range of the horn and the 4x4 ESAF. The 4x4 ESAF prototypes did not work for reasons explained later. Figure 5.4 shows simulated and measured comparison results between the feedhorn and ESAF. Once again, the 4x4 is simulation only and SNR difference is due to LNA NF and other issues are discussed below. In figure 5.4(a), the SNR variation between the 4x4 and 2x4 ESAF is explained at the end of section 4.3.3.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>horn</th>
<th>2x4 ESAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>11.85</td>
<td>11.9</td>
</tr>
<tr>
<td>11.9</td>
<td>11.95</td>
<td>12</td>
</tr>
<tr>
<td>12.0</td>
<td>12.05</td>
<td>12.1</td>
</tr>
<tr>
<td>12.1</td>
<td>12.15</td>
<td>12.2</td>
</tr>
<tr>
<td>12.2</td>
<td>12.25</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

**Figure 5.2:** Measured SNR as a function of frequency.

The 2x4 ESAF SNR in figure 5.4(b) is variant because of the way the test was performed. In order to simplify and shorten testing (manual beam weight optimization takes time), beam weights were only updated once the SNR fell below 4.5dB. Video can be de-
Figure 5.3: 2D (azimuth and elevation) steering plots. (a) The 2D plot for the horn. (b) The 2D plot for the 4x4 ESAF.

coded, without glitch, from about 4dB SNR and higher. The red curve shows what the SNR would look like if the weights were optimized at every azimuth point. Also, note that only 5 gain values were used to optimize weights, so similar to figure 4.6, with only a few number of beam states, dips appear between element pairs.

Both the 2x4 and 4x4 ESAF show increased steering range compared to the feedhorn, despite having lower SNRs. The 2x4 doubled the range the system was able to receive streaming video. The 4x4 in simulation had four times the scan area and according to the 2x4 results, it would most likely do the same in measurement. These low-cost ESAFs can, in fact, steer the antenna beam.

5.2 Calibration, Acquisition, and Tracking

Creating an ESAF that could steer a beam was only one objective. The significant advantage of an ESAF is being able to point, acquire, and track while maintaining a link if the satellite or the ground platform was moving. The purpose of this section is to show how
the 2x4 ESAF was calibrated and set up to acquire a satellite and track it as the dish was moved east to west and west to east.

The set up for tracking was almost the same as above except that a feedback loop was added to the system. Figure 5.5 shows a block diagram and picture of the feedback system. The signal from the LNB was split between the receiver and the feedback chain. The receiver supplies voltage to the LNB, so a DC block was required before the amplifier. The power detector had a range of operation in which it is linear between signal power (dB) and output voltage. The amplifier boosted the signal into the required range. For tracking, the system only needed to see a satellite and did not care about the transponders and video; the filter was used to focus on one transponder and remove the other signals from the view of the power detector. This cleaned up the power detector output quite a bit. The power detector output ranges between 0.5V-2.1V and is inversely related to input power. The ADC has a voltage ceiling of 5V. To increase the resolution of the ADC to the power detector output, an amplifier was placed after the power detector. This increased the output to 1.2V-5V. The ADC was part the existing μController. Because of this integration, the μController
could record the sample, perform calculations, and act accordingly. The picture shows two \( \mu \)Controllers, one was the ESAF controller and the other simply streamed constant samples of the power detector output to the computer for the user to see.

Figure 5.5: Feedback system to report signal quality to the \( \mu \)Controller.

Figure 5.6 shows the entire system in a test bench setup. For a product, everything would have to be in one box. Starting from the top, the dish with ESAF can be seen. The cables going down and to the left are power cables for the ESAF electronics. The cable going down and to the right is the VGA control cable from the DACs. There is a satellite receiver on top of the TV (left side). At the bottom left is the DC block and amplifier. It is difficult to see, but at left center is the micro strip coupled line filter. The power detector cannot be seen, but the brown board (right center) is the op-amp amplifying the power detector output. The rest are cables for power or passing the detector voltage between the two \( \mu \)Controllers.

5.2.1 Calibration

Before any tracking could occur, the system had to be calibrated. Calibration means different things for different arrays. For this ESAF, calibration was taking a measurement
of the signal when no satellite is present. In other words, the array calibration measured the noise response of the different beam weights. The low-cost system implemented here did not have a signal processing unit to calculate correlation matrices or other parameters that could be used to separate noise from signal, so the system had to understand what noise only looks like coming from the power detector when a set of beam weights was applied to the array.

The calibration process required a discrete set of predefined beam weights that were stored on the computer and $\mu$Controller. The predefined beam states can be generated from a model only allowing values that are achievable with the DACs and VGAs or manually found by running an on-dish test and tuning the weights. The list on the right of figure 5.7 was obtained by pointing the dish to boresight and moving the dish east or west by set
increments and manually finding the optimal beam weights to maximize SNR. These weights were then recorded in a text file arranged from most western state to most eastern state and uploaded the \( \mu \)Controller. Figure 4.14(a) shows a different set of states uploaded, but the idea is the same.

The first step to calibrating the array was to roughly point the dish and align the feed as described in section 5.1. The 2x4 ESAF only had a 4\(^\circ\) steering range so that target recognition would not have to be implemented and steering within that range would limit the chance of picking up an adjacent satellite. The dish had to be close to boresight so the ESAF could steer the full range and not get confused with neighboring targets.

Next, the noise response was measured. Because the satellite cannot temporarily move from orbit to measure noise only response, the dish was lifted in elevation to point at sky only. Since most of the beam pattern is directed to the sky this worked well, but the ground profile changed and therefore spillover noise changed slightly. Once lifted, the \( \mu \)Controller measured the noise only power detector output for each beam state and stored them for later use (clicking on Measure Background button). This was done by setting the VGAs to the weighted gain and sampling the power detector, then moving to the next state. The top center of figure 5.7 shows a plot of the measured background at each state from west to east. The background noise measurements are called “off signal” because the dish is pointed away from all signals, even as the ESAF scans. After finishing the scan, the dish was lowered back into position and the calibration was done. Now acquisition could begin.

5.2.2 Acquisition

Acquiring the satellite worked in much the same way as calibration. The system swept all the loaded beam states and recorded the power detector output. The top left plot of figure 5.7 shows what this output looks like. This record is called “on signal” because the dish was in a position where, as the ESAF scans, it would cross the satellite’s signal. The off signal and on signal plots look very similar. The two measurements are expected to look similar because when the ESAF is steering away from the satellite it should be picking up only noise. As can be seen, they are not exactly the same and this is because the dish still has beamwidth and it picks up small amounts of signal when steered away.
The next step in acquiring the satellite was to pick the best state. When pointing a horn fed dish, often signal strength is enough to know that the satellite has been acquired and this is true because as the beam peak approached the satellite signal, the strength of that signal grows. ESAFs have VGAs that change the signal strength independent of a strong satellite signal or not. If the decision was solely based on signal strength, then the acquisition process shown in figure 5.7 would have picked the most western state because it has the highest signal. However, in this test the dish was close to boresight. In order to find the correct state, the \( \mu \)Controller takes the off signal measurements and divides them by the on signal measurements to calculate a power detector SNR (power detector has an inverse relation with signal, thus \( N/S \) instead of \( S/N \)). This calculation removes the effects of the gains because both noise and signal are scaled by the weights. The lower plot in the figure shows what this calculation looks like for each state. Now there is an obvious peak showing which state pointed to the satellite. The \( \mu \)Controller then set the VGAs to that state and the link was established. After the system was calibrated and the satellite was acquired, the system switched to tracking mode.

5.2.3 Tracking

The ESAF was designed to be simple and, in the case of this ESAF, only steered in one dimension. The system was further simplified by having predefined states to search through. This made tracking pretty simple, but also created problems with occasionally losing signal because a state did not exist for a given dish position.

The simplest way to track is to understand the way the target will move. Whether the dish or the satellite is moving, it is pretty much guaranteed that the satellite will move next to where it just was in some azimuth and elevation direction. Re-scanning the entire steerable space every time the signal drops will be sure to find the satellite, but it is very inefficient and the link will be closed most of the time. The UI did provide a “Run States/Max Hold” option which did just that; it ran a new acquisition phase every time the signal quality drops below a certain tolerance. Knowing that the first place to look should be in neighboring beam positions makes for a much more efficient algorithm. This algorithm is called the “3 Pt. Search,” or “5 Pt. Search” in the case of 2D steering.
Figure 5.7: Signal acquisition report. (Right) Preset beam weight list loaded into the µController. (Top Center) Power detector output from calibration step. (Top Left) Power detector output from acquisition step. (Bottom) Calculated power detector SNR.

The 3 Pt. Search worked by recording the SNR at the current state and then setting the VGAs to the next west and east states, calculating their SNR, and comparing them to the current state. If either the west or east neighbor was better, then the ESAF was set accordingly. This continued to repeat. The benefit of this algorithm was that as long as the states are close enough together that beams overlap, the signal would fluctuate, but was never lost. The link was maintained while tracking. The states had to be far enough apart that there was a definite better state. Using this tracking algorithm, the satellite was tracked as the dish is moved within the 4° range.
5.3 Challenges

The system is still very much in its youth and as such there are many limitations and challenges. Below is a list of issues that arose.

- The current ESAF’s major challenge is the SNR. It is much lower than the horns. While much of that is attributed to the LNA, there are still some sources of noise that are not accounted for. There is some difference between simulation and measurement that can be seen in the horn and other antennas of about 2.5dB (figures 3.3 and 3.5), but the 2x4 ESAF is about 4.2dB (figure 5.4), which is almost 2dB more than expected. A possible cause is that the system has a higher NF than 2.1dB due to impedance mismatch or NF of the VGA is too high to be offset by the LNA gain. Another cause, and very likely, is the signal coming out of the ESAF and LNB is too high and being clipped by the modem. The ESAF contributes an additional 30dB or more gain to the system.

- The 4x4 ESAF came back from assembly non-functioning. The board fabrication was fine, but something happened with the components placement. One of the boards came back with a short and could not even be powered. The other could be powered, but had at least one non-responsive VGA in every 2x2 sub-array and therefore could not get proper illumination. The VGAs are very small and have three pins under them, the center pin being a GND pad. A little shift towards the power pin will short the board and a little shift towards the control pin will cause the chip not to function. It is also possible the LNA overheated during solder reflow and burned out. More diagnostics are required to pinpoint the failures.

- Calibration never returned the same results for the same set of states. When hooked up to the system, the power detector is noisy. The frequency response of the op-amp helped mitigate that, but it is still noisy. Sometimes the calibrations will be within an allowable range, but sometimes they will result in false positives when tracking.

- There are lots of cables and connectors, and each cable and connector represents a point of failure. This is a prototype issue and more of an inconvenience than a challenge.
It is annoying when running a test and a control wire pops out causing unexpected results.

- Despite all attempts to avoid neighboring satellites, when tracking to edges of the steerable range, the test satellite signal will be low. If the signal is too low compared to the neighboring satellite, the system will try to track the neighbor. This could be avoided with target recognition by getting a true SNR from the receiver, which is aware of the satellite it is receiving.

- There is a slow settling time in the system. Most likely due to the power detector charging and discharging. So the µController must be delayed before getting a new power detector sample. Running calibration too fast meant that the power level from one state to the next would carryover, ruining the calibration. This was solved with the delay. When tracking this was problematic because, even though the ESAF could be updated fast enough to track high speeds, the power carryover would cause false positives and run the steering in the wrong direction. By the time the system recovered, the target was out of reach and an acquisition step was required. When shaking the dish, the ESAF could do a little better than the horn in locking signal, but nothing that would suggest it would do better in a wind storm.
Chapter 6

Conclusion and Future Work

Today’s communication industry is evolving at an exponential rate and the communication systems of tomorrow must reflect that growth. The need for bandwidth increases and communication bands are going higher in frequency. These new antenna systems get harder and harder to align. More systems are becoming mobile and being subjected to versatile environments. These communication links must be closed and steerable arrays are becoming no longer just a nice feature, but a necessity to point the system, close the link, and then keep it closed.

This work claims that feedhorns could be replaced with smaller, lighter, and cheaper planar antennas. It claims that an electronically steered array feed (ESAF) could steer a beam without mechanics, acquire a satellite, and track that satellite in the event that it or the ground dish is moving. It also claims that all this could be done in a low-cost platform that would be affordable for consumers.

Chapter 3 gave examples of passive feed antennas that can compare to a feedhorn and, in some figures of merit, could outperform the feedhorn. They are easy to customize for the reflector and can even feed low $f/D$ dishes without using subreflectors.

Chapter 4 covered the design of new low-cost ESAFs. These ESAFs could improve SNR by forming beams ideal for the reflector and they could steer. New ideas were discussed to lower the cost of design and simplify the beamformer electronics. A study was performed to see how far limits could be pushed and what the trade-off would be for doing so. Lastly, the chapter talked about a low-cost controller for the array that could be integrated into a product design.

Chapter 5 demonstrated that a commercial ESAF is feasible and that it is possible to maintain a link independent of motion. The ESAF was able to double the steerable range of
a standard dish system. Also, by incorporating a simple feedback loop, the array was able to acquire and track a satellite as the dish moved. This acquisition and tracking algorithm could easily be added to the controller already being used to adjust the ESAF. Chapter 5 also talked about some of the challenges that will need to be overcome.

6.1 Future Work

The SatCom group at BYU is among the first in published literature to explore high efficiency planar antennas and low-cost electronically steerable arrays that could be used to feed dish reflectors. This research is very much in its early beginnings, and as such, there is still a lot of work to do. This thesis presents a foundation to build upon and much further research is required to completely change the SatCom industry. The following are just a few areas, specific to continuing this thesis work, which should be explored.

Planar antennas have great potential and their performance is admirable, but further development is required to push the bounds of efficiency. Getting antennas to match feedhorn performance would be amazing. Beyond efficiencies is the antenna polarization. SatCom requires linear and circular polarized antennas. Development into high efficiency planar antennas that are circularly polarized would be ground breaking work.

The first step in making the ESAF practical for SatCom applications is to increase SNR by decreasing loss and noise. This would require a new LNA and a miniaturized version of it for making larger arrays or saving board real estate. The electronics in an array are one of the most limiting factors in array development. Research into specialized IC designs that are specific to steerable arrays would make these antennas more practical and open a whole arena for new active array type antennas.

The steering and tracking features for the ESAF need to be improved. The ESAFs in this work require a lot of manual turning and optimization. Algorithm and model research should be performed to come up with beam weights automatically, whether found beforehand or optimized on the fly. High end arrays have signal processing units to derive weights, but a question to answer is whether or not there exists a low-cost solution to automated beam weighting. The other end of the steering and tracking features is the feedback system. The current system is too slow and lacks a lot of information that would be valuable for array
control. Further development is required to maximize information return and speed using a low-cost feedback system.

While this work focused mainly on steering and tracking over a small range, further research could go into expanding the steering range. This may involve target recognition, switching between multiple targets, or locking on one target and tracking it over a greater range. Expanding the steering range would also require further investigation into beam weighting and determining if greater steering ranges require different conditions on weights and possibly, phase shifters. Expanding the range would create a solution for dishes on a boat where the boat will rock on waves.

There are many other ESAF features to explore and see if they can feasibly be done in a low-cost format. Some of these features include: developing a multi-beam ESAF, incorporating polarization switching and polarization skew correction, implementing a feed that could switch between linear and circular polarization. Finally, research could go into new reflector designs that optimize the ESAF’s abilities.
Bibliography


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Appendix A

Additional Figures

Figure A.1 shows the SNR pattern vs steering angle for all the measured passive antennas. With the exception of having different SNR levels, the angular range of all the antennas is about the same.

![SNR Beamwidth](image)

**Figure A.1:** SNR as a function of azimuth angle for measured passive antennas. This is more-or-less an SNR beamwidth.
Appendix B

Matlab Code

B.1 Offset Dish Code

The following code generates an offset dish model and calculates dish parameters according to the math developed in chapter 2.

clear all
clc

Dl = 940;     % (mm) Diameter of large axis
Ds = 850;     % (mm) Diameter of short axis
f = 510;      % (mm) Focal Length of Parent

thetaoff = acos(Ds/Dl);
y0 = 0;
x0 = 2*f*tan(thetaoff);
z0 = (x0^2+y0^2)/(4*f)-f;
P0 = [x0 y0 z0];

% XY Projection
phi = (0:90/10:360)*pi/180;
drad = (Ds/2)/10;
rad = 0:drad:(Ds/2);
X = rad'*cos(phi)+x0;
Y = rad'*sin(phi)+y0;

% Offset Dish
Z = (X.^2+Y.^2)/(4*f)-f;

% Parent Dish
Rparent = Ds/2+x0;
foD_parent = f/(2*Rparent);
drad = Rparent/10;
rad = 0:drad:Rparent;
Xp = rad'*cos(phi);
Yp = rad'*sin(phi);
Zp = (Xp.^2+Yp.^2)/(4*f)-f;

% Cone
Pb = [x0-Ds/2 y0 ((x0-Ds/2)^2+y0^2)/(4*f)-f];  % Top rim point
Pt = [x0+Ds/2 y0 ((x0+Ds/2)^2+y0^2)/(4*f)-f];  % Bottom rim point
Ps = [x0 y0+Ds/2 (x0^2+(y0+Ds/2)^2)/(4*f)-f];  % Side rim point
% Cone half angle along Dl axis
thetas = 0.5*acos((norm(Pb)^2+norm(Pt)^2-Dl^2)/(2*norm(Pb)*norm(Pt)));

% Cone rotation angle
theta0 = acos((norm(Pt)^2+f^2-norm(Pt-[0 0 -f])^2)/(2*norm(Pt)*f))-thetas;
if theta0 == 0
    Pc0 = [0 0 -f];
else
    tmp = 2*f*(-cos(theta0)+1)/sin(theta0);
    Pc0 = [tmp 0 (tmp^2+0^2)/(4*f)-f];
end

% Cone half angle along Ds axis (symmetric cone: should = thetas)
thetass = acos((norm(Ps)^2+norm(Pc0)^2-norm(Ps-Pc0)^2)/(2*norm(Ps)*norm(Pc0)));
foDeff = (1+sqrt(abs(tan(thetas))+1))/abs(4*tan(thetas));

% Outputs
disp('Focal Length: ' num2str(f))
disp(['Parent Diameter: ' num2str(2*Rparent)])
disp(['Parent f/D: ' num2str(foDparent)])
disp(['Focal Point from Bottom: ' num2str(norm(Pb))])
disp(['Focal Point from Top: ' num2str(norm(Pt))])
disp(['Focal Point from Side: ' num2str(norm(Ps))])
disp(['Tilt Angle so Beam Aligns with Horizon: ' num2str(90-thetaoff*180/pi)])
disp(['Illumination Angle (Large Axis): ' num2str(2*thetas*180/pi)])
disp(['Illumination Angle (Small Axis): ' num2str(2*thetass*180/pi)])
disp(['Effective f/D: ' num2str(foDeff)])
disp(['Theta Star: ' num2str(thetas*180/pi)])
disp(['Theta 0: ' num2str(theta0*180/pi)])