Tracking Antenna System for the nCube project ground station
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Sammendrag
I denne hovedoppgaven har jeg sett på ulike løsninger for et tracking antenna system for nCube satellitt prosjekt.
Etter at jeg har vurdert tilgjengelig utstyr har jeg valgt en av oppsettene for et tracking system jeg har anbefalt og har simulert den i Simulink.

Jeg har også testet nCube bakke segment antenna system polarisasjon, G/T forhold og har foreslått en metode for test av antenna gain.

Abstract
In this diploma report I have looked at different solutions and made recommendations for hardware and design of a tracking antenna system for the nCube satellite project.
After having evaluated three alternative designs for a tracking system I have chosen one of them and simulated it in Simulink.

I have also performed tests on the nCube ground station antenna system polarization, overall system sensitivity and recommended a technique for test of antenna gain.

Norske stikkord
nCube, tracking system, monopuls, hybridnettverk, monopuls detektor, Simulink, antenna polarisasjon test, G/T test, antenna gain test

Keywords
nCube, tracking system, monopulse, comparator network, monopulse detector, Simulink, antenna polarization test, G/T test, antenna gain test

Preface

The nCube satellite project was started by Andøya Rocket range (ARS) and the Norwegian Space Centre (NRS). The goal of the project is to build competence in space related fields within teaching institutions and among students, while at the same time building competence for future Norwegian satellite activity.

The layout of the satellite is based on the Cubesat concept, developed by Stanford University in the late 1990s. The Cubesat satellite is, as its name indicates, a cubical satellite measuring 10x10x10 cm, with a mass no greater than 1 kg. This standardized layout makes for a low cost, easily launched system, but also presents a few challenges, such as designing the proper payload within the physical limitations of the spacecraft.

The main idea of the project is to design, build, test and launch a small satellite based on student work at Norwegian universities and colleges. The project is split into 7 subgroups, where NTNU looks at the areas of Structure, Power, Attitude Determination and Control Systems, Communications and Downlink, On Board Data Handling, and technical framework for payload. HIN looks at ADCS, Power and Ground Segment/Uplink, and NLH will studies payload and applications.

The primary mission of the nCube satellite is defined by the Agricultural University of Norway (NLH), and will consist of tracking migration of animal populations, mapping grazing land, snow melting, woodlands etc.
After completion and testing, the satellite will be launched from a Ukrainian launch site and brought into a polar orbit 600 km above the Earth.

A suitable amateur ground station has been constructed during the time of this project by the Ground Segment Group. One of the main functions of the ground station antenna system is to maintain the axis of the antenna system beam in the direction of the satellite in spite of movement of the satellite or the antenna system itself. As a member of the Ground Segment Group I was given the task to propose a design for a tracking system for the nCube project.

Acknowledgements

I would like to thank my supervisors Frank Vedal and Per Johan Nicklasson for all the knowledge and support during this work, and for giving me an opportunity to work on this project.

I would also like to thank technical coordinator of this project Egil Eide for his essential role in this project. Much of the material in this thesis is based on his ideas and invaluable hints.

It was my pleasure to have such a nice team to work with during this project, so I would like to thank everyone in the Ground Segment Group.

Special thanks to Arne Bjørk and library personnel who helped a lot in finding necessary information about the project problem.

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Summary

Satellite tracking methods have gone through several developments and changes. The fact that satellites drift from their supposed orbits due to lunar, solar and earth gravity and radiation pressures requires several correction techniques to maintain a continuous flow of information between the satellite and the earth station. Usually large drifts are corrected by the satellite controllers on board which fire some reaction equipment to keep it on track.

The earth station might still see some minor drifts that require special compensation methods in order to maintain accurate tracking.

The subject of this diploma report is to propose a design of an antenna tracking system for the nCube satellite ground station.

The main tracking techniques can be stated as follows:

- *Programmed tracking*
- *Step tracking*
- *Conical scan*
- *Sequential Lobing*
- *Monopulse tracking*

Programmed tracking has already been chosen for tracking the nCube satellite, [GSEG-03]. The best solution for a tracking system could be a combination of programmed- and step- tracking techniques. But because of lack of information about step tracking system configuration I had to move on to other methods in order not to use too much time for information search.
Because of the requirements for the antenna system both conical scan and sequential lobing techniques are impossible to implement with the ground station antenna system we have. To buy the required antenna system will be too expensive.
The last option was a monopulse tracking technique. This technique is the most accurate among the ones stated above, but at the same time the most complicated one. It is usually used in complex and expensive tracking systems which are used for example for military reasons.

After having studied the basics of this technique I have made a decision to try to simplify this system for our project and make a suggestion of the hardware to be used.

After evaluating available hardware I have recommended three different alternatives for a monopulse tracking system which may be used to track almost any object communicating within the amateur bands.

Since there has been no time to assemble and test either of the solutions I have simulated one of them in MATLAB.

This project report also includes measurement and calculation of the receiving system figure of merit (G/T), as well as measurement of the ground system antenna polarization pattern and antenna system gain.

1.0 Introduction

This diploma report is one of several diplomas which are all parts of the nCube project. To solve such a complicated and time consuming problem, the project has been divided into several smaller parts:

- Ground Segment Communication/ Power
- Space Segment Communication
- Space Segment Power
- Attitude Control and Determination
- On Board Data Handling
- Structure
- Payload

The goal of this particular project is to design a tracking system for the ground station to track the nCube satellite.

The tasks I had can be divided into following areas:

Tracking system

- Choose a tracking technique
- Develop the theoretical background for the chosen tracking technique
- Find equipment to implement the chosen tracking system
- Simulate the system in MATLAB

Ground Station Antenna System

- Measure the figure of merit (G/T)
- Measure antenna polarisation pattern
- Measure antenna system gain

2.0 Terminology and Definitions

2.1 Definition of Monopulse

The following definition, taken from IEEE Standard 686- 1982, *Radar Definitions*, can be given:

"A technique in which information concerning the angular location of a source or target is obtained by comparison of signals received simultaneously in two or more antenna patterns, as distinguished from techniques such as lobe switching or conical scanning, in which angle information is derived from a series of sequential antenna patterns. The simultaneity of the patterns makes it possible to obtain a two- coordinate angle estimate from a single pulse, although multiple pulses are usually employed to improve the accuracy of the estimate, provide Doppler resolution, or simplify the processing. The monopulse principle can be used in continuous- wave as well as pulsed radar, and also in non- radar applications."

Monopulse is most commonly found in tracking radars (or in the tracking mode of multifunction radars), but can also be used for special search applications. It can be used in a single angle coordinate or in both coordinates.
Complete three- dimensional tracking of a target requires range as well as two angles. Monopulse is not involved in range tracking, but does require as input from the range tracker in order to track a target efficiently in angle.

Certain terms commonly used in monopulse need to be defined or explained, because, even if they are familiar in general usage, they may have specialized meanings when applied to monopulse, and these meanings may differ from the literal interpretations.

2.2 Sum and Difference patterns

Pointing direction is generally defined in terms of orthogonal angular coordinates off boresight, namely, elevation (up and down) and azimuth (right and left). The angular errors off the desired pointing angle are denoted as Δaz for the azimuth error, Δel for the elevation error and the total received signal is usually denoted as the sum signal, Σ. These patterns are commonly referred to as "sum" and "difference" even when these names are not literally correct, because they have the same shapes and serve the same functions as true sum and difference patterns.

2.3 Traverse and Azimuth

As it has already been mentioned, the sum, elevation difference and azimuth difference patterns are formed, but actually it is the traverse difference pattern that is formed, not the azimuth.
Traverse angle differs from azimuth angle: traverse is measured in the slant plane containing the line of sight to the target, while azimuth is measured in the horizontal plane.
Almost all antenna mounts for tracking radars and antennas are azimuth- elevation mounts where the axes are designed for rotation in those two coordinates. The monopulse output, however, responds to the displacement of the target from the antenna boresight axis in traverse and elevation, not azimuth and elevation.
Let A and α' be the azimuth and traverse displacements respectively of the target from the boresight axis, and E be the elevation angle of the target measured upward from the horizontal plane. These angles are illustrated in figure X.X from which the following relation can be derived:

$\sin A = \sin \alpha' \sec E$ **(eq 2.3.1)**

which for small A is approximated by

$A \cong \alpha' \sec E$ **(eq 2.3.2)**

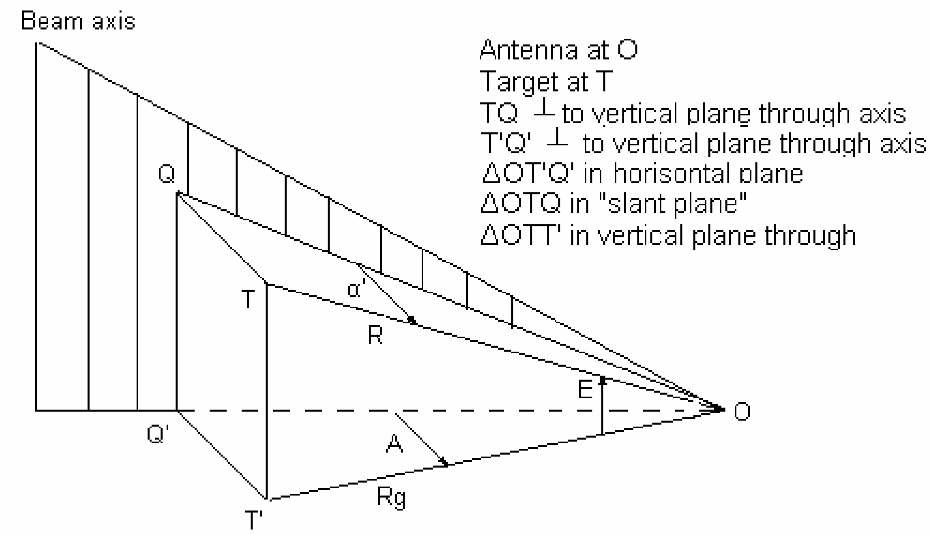


Figure 2.3.1: Geometric relations among angles: azimuth (A), elevation (E) and traverse (α').

Equation X is the basis of the secant correction in mechanically steered tracking systems. The monopulse traverse output is approximately proportional to α', but the servo requires an input approximately proportional to A. The conversion is accomplished by generating a multiplying factor proportional to the secant of the elevation angle. This secant correction can be done by a secant- wound potentiometer or by computer.

2.4 The monopulse output as a complex ratio

Monopulse processing involves voltage amplitude ratios, phase differences, or both, rather than values of individual amplitudes or phases. If the angle indication depended on individual values, it would vary with the nature, size, and range of the target, but voltage amplitude ratios and phase differences depend only on target angular location.

Any alternating voltage, current, or electromagnetic field component can be represented mathematically by a complex number, with can be expressed in the form of magnitude and phase, or in the form of a real part and an imaginary part. In general, the ratio of two voltages means their complex ratio. In monopulse, the two voltages involved, for each coordinate, are usually the difference voltage in that coordinate and the sum voltage, which is common to both coordinates. The phasor voltages (complex envelopes) of a monopulse difference, *d*, and sum ***s***, can be expressed as

$$\begin{aligned} d &= |d| \exp(j\delta_d) \\ s &= |s| \exp(j\delta_s) \end{aligned} \quad \textbf{(eq 2.4.1)}$$

where $\boldsymbol{\delta_d}$ and $\boldsymbol{\delta_s}$ are phase angles relative to any arbitrary common reference. The complex ratio is

$$\frac{d}{s} = \frac{|d|}{|s|} \exp\left[j(\delta_d - \delta_s)\right] = \frac{|d|}{|s|} \exp(j\delta) \quad \textbf{(eq 2.4.2)}$$

where $\boldsymbol{\delta}$ is the relative phase:

$$\delta = \delta_d - \delta_s \quad \textbf{(eq 2.4.3)}$$

Thus the complex ratio has a magnitude equal to the ratio of the magnitudes of the two voltages and a phase equal to their relative phase.

Ideally, the relative phase *δ* of *d* and ***s*** from a single point target is either 180° or 0°, depending on the sense of the angular displacement. Under idealized conditions the ratio *d/s* is pure real. In practice, however, *d* and *s* can have any relative phase, because of noise, interference and equipment imperfections. Therefore *d/s* must be regarded as a complex quantity.

Using mathematical equivalence, we can expand equation **2.4.2** as follows:

$$\frac{d}{s} = \frac{|d|}{|s|}e^{j\delta} = \frac{|d|}{|s|}\cos\delta + j\frac{|d|}{|s|}\sin\delta \quad \textbf{(eq 2.4.4)}$$

Thus the real and imaginary parts of *d/s* are

$$\mathrm{Re}(d/s) = \frac{|d|}{|s|}\cos\delta$$

$$\mathrm{Im}(d/s) = \frac{|d|}{|s|}\sin\delta$$

(eq 2.4.5) a), b).

The output of the monopulse processor is only the real part (in-phase component) of the complex ratio *d/s*. The imaginary part can be extracted, if desired, but normally this is not done, because the target ideally contributes only to the real part, while the imaginary part is due to noise and other disturbances. What means that under idealized conditions, when the relative phase of *d* and ***s*** is either 0° or 180°, the real part represented by the equation X7 a) is the same as *d/s* itself.

In some types of monopulse systems, the relative phase of *d* and ***s*** under idealized conditions is ±90° (quadrature phase) instead of 0° or 180°. In that case the ratio *d/s* is pure imaginary. The quadrature- phase relation can be converted to the in- phase relation by phase shifting either *s* or *d* by 90°. Alternatively, the processing can easily be modified by replacing the real part of the ratio (cosine factor) by the imaginary part (sine factor).

3.0 Components used in monopulse system

Certain components are either unique to monopulse, or they are designed or used in a special way for monopulse. A few important components of these types are discussed here.

3.1 Comparator/Summation network

A typical monopulse feed consists of four horns or antenna elements, from which a sum and two differences can be obtained. This requires use of certain passive microwave devices known as hybrids or hybrid junctions of which there are several different types.

Hybrids used in monopulse have four ports- two for inputs and two for outputs. If two voltages *v1* and *v2* are applied in the proper way at the input ports, outputs proportional to their sum and difference will appear at the output ports. Three important types of these devices are the *Magic –T*, the *hybrid ring junction* (also known as rat race) and the *3dB directional coupler* (also known as a quadrature hybrid or 90° hybrid).

To be precise, the outputs of hybrids are not equal to the sum and difference, but are proportional to them:

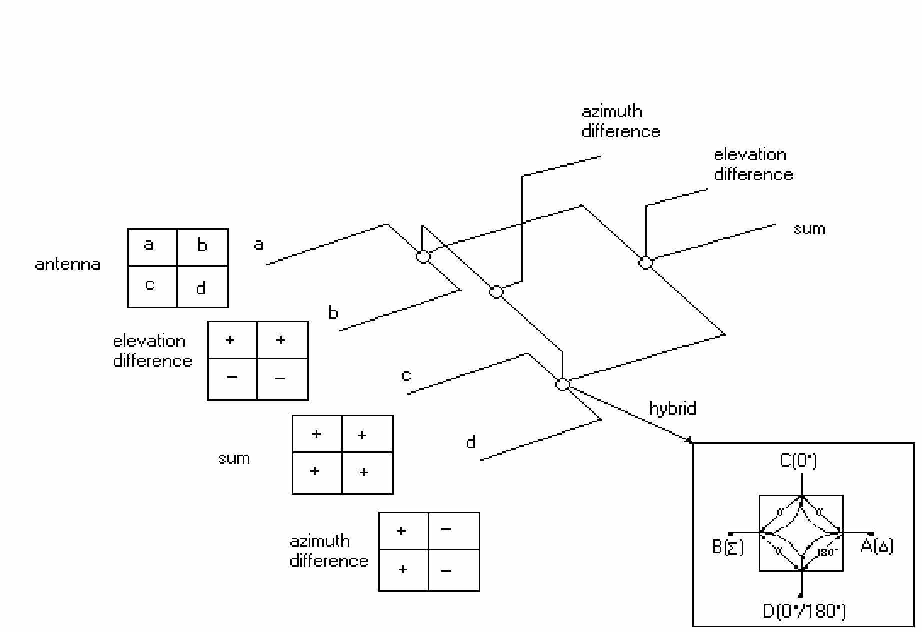
$$s = k(v_1 + v_2) \quad d = k(v_1 - v_2) \qquad \textbf{(eq 3.1.1)}$$

The proportionality constant ***k*** turns out to be $1/\sqrt{2}$, [BRO-88], as can be verified by squaring both sides of the two equations and adding to obtain

$$s^2 + d^2 = v_1^2 + v_2^2 \qquad \textbf{(eq 3.1.2)}$$

This is as expected, because the device is passive and nearly lossless and thus total output power must equal total input power. Since the proportionality constant is the same for the sum and the difference, it does not affect their ratio.

The whole assembly of hybrids, phase shifters (if needed), and waveguide sections needed to convert the signals from the individual feed horns or antenna elements into a sum and two differences is called the comparator. Figure 3.1.1 is a schematic diagram of an illustrative comparator of a monopulse tracking system with feed consisting of four antennas.



Figur 3.1.1: Comparator for four- antenna monopulse feed using magic –T hybrids, (factors of $1/\sqrt{2}$ and ½ omitted).

3.2 Monopulse processor

The monopulse processor is that portion of a monopulse system that operates on the voltages derived from the antenna patterns to produce the monopulse outputs. In most cases the voltages on which the processor operates are the sum and the two differences, although in some amplitude- comparison systems the voltages are those from the squinted beams.
The desired output for amplitude- comparison monopulse is usually the real part of the complex ratio d/s, expressed by equation X7 a), and for phase- comparison monopulse the desired output is the imaginary part, expressed by equation X7 b).

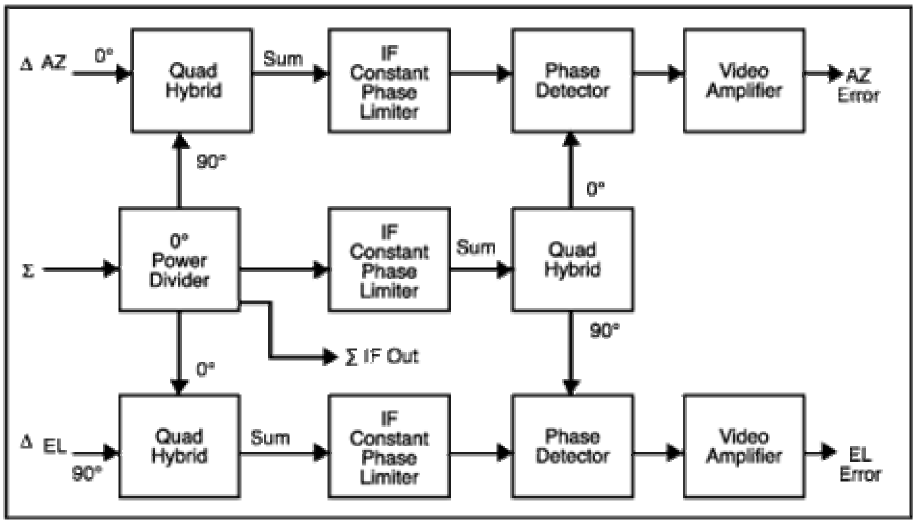


Figure 3.2.1: Block diagram of a monopulse detector, MMDQ series from Miteq [22].

The output from the monopulse processor can be used open- loop, in combination with the known direction of the beam axis, to determine target angle, or the output can be fed back in a closed loop to control the direction of the beam so as to keep the axis pointed as closely as possibly toward the target.
In some cases, to improve accuracy, open- loop and closed- loop operation are employed simultaneously, the open- loop output being used as a fine correction to the closed- loop angle indication.

3.3 Servosystem

Servo is the portion of the tracking system that receives as its input the tracking error voltage and performs the task of moving the antenna beam in a direction that will reduce to zero the alignment error between the antenna axis and the target.

3.3.1 Antenna mount

Various types of mounts are used for monopulse. The most common type is the elevation- over- azimuth two- axes mount. Because of the geometric relations expressed by equations X1 and X2, azimuth rates and accelerations can be quite large when the target is at high elevation, even when the traverse rates and accelerations are moderate. The mounts must have sufficiently powerful drives to follow the target motion.

3.3.2 Antenna

Many different types of antennas can be used in monopulse system, but the three main categories of antennas used are: lenses, reflectors and arrays, each of which can be subdivided into various types.

4.0 One- and Two- Channel Monopulse Systems

4.1 One- Channel Monopulse system

Monopulse systems can also be constructed with fewer than the conventional three IF channels. This is accomplished by combining the sum and the difference signals by some means so that they may be individually retrieved at the output. These techniques provide some advantages in AGC or other processing techniques, but at the cost of SNR loss or of cross coupling between azimuth and elevation information.

A single- channel monopulse system called SCAMP (single- channel monopulse processor) provides the desired constant angle error sensitivity by normalizing the difference signals with the sum signal in a single IF channel, as shown in Figure X.X.

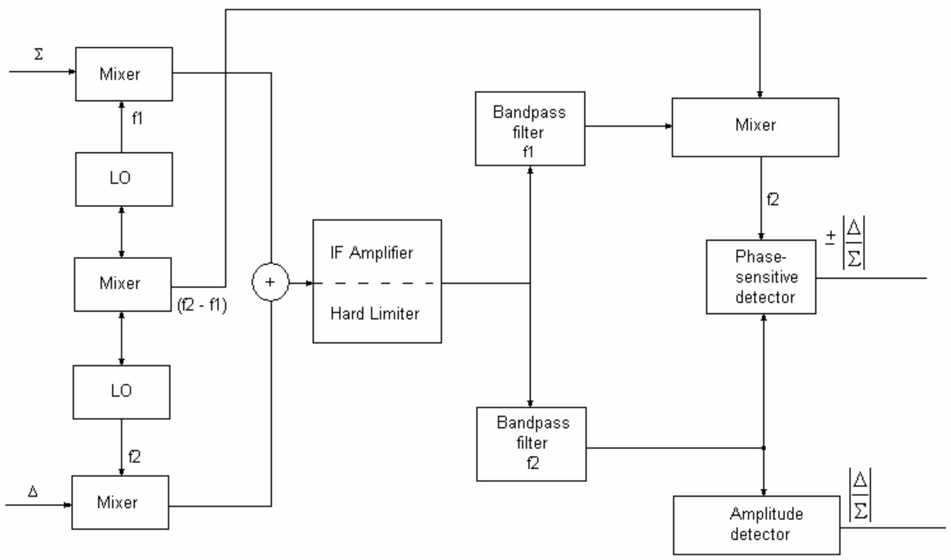


Figure 4.1.1: Block diagram of SCAMP, a single- channel monopulse tracking system, demonstrating angle tracking in one coordinate, [SKO-90].

The signals are each converted from RF to different IF frequencies by separate local oscillators (Los) of different frequencies for each signal. They are amplified in a single IF amplifier of sufficient bandwidth for all three signals at different frequencies. At the IF output the signals are hard- limited and separated by three narrowband filters. The signals are then converted to the same frequency by beating two of the signals with the frequency difference between their Los and the LO of the third signal. The angle- error voltage is then determined by either a conventional phase detector or an amplitude detector. The effect of AGC action and normalizing is performed by hard limiting which causes a weak signal suppression of the difference signal.

Performance in the presence of thermal noise is about equal to that of the three- channel monopulse. However, the limiting process generates a significant cross-coupling problem, causing a portion of the azimuth- error signal to appear in the elevation- angle- error- detector output and elevation error to appear in the azimuth-angle- error- detector output.

4.2 Two- Channel Monopulse System

A two- channel monopulse receiver may also be used by combining the sum and difference signals at RF, as shown in Figure 4.2.1.

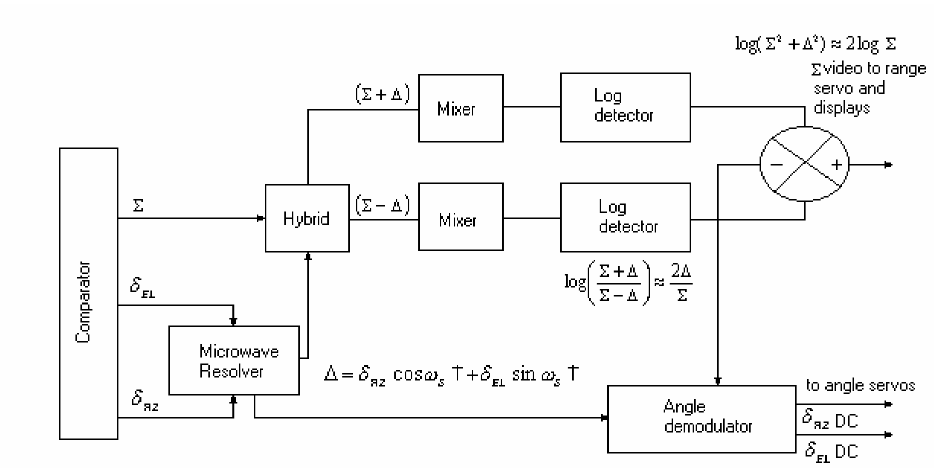


Figure 4.2.1: Block diagram of a two- channel monopulse system [SKO-90].

The microwave resolver is a mechanically rotated RF coupling loop in circular waveguide. The azimuth and elevation difference signals are excited in this guide with E-field polarization oriented at 90°. The energy into the coupler contains both difference signals coupled as the cosine and sine of the angular position of the coupler, $\omega_s t$, where ω_s the angular rate of rotation. The hybrid adds the combined difference signals Δ to the sum signal Σ.
The advantage of two channels with opposite- sense angle error information on one with respect to the other is that signal fluctuations in the received signal are canceled in the post detection substractor at the IF output which retrieves the angle- error information. The log IF performs essentially as instantaneous AGC, giving the desired constant angle-error sensitivity of the difference signal normalized by the sum signal. The detected Δ information is a bipolar video where the error information is contained in the sinusoidal envelope. This signal is separated into its two components, azimuth- and elevation- error information, by an angle demodulation. The demodulator, using a reference from the drive on the rotating coupler, extracts the sine and cosine components from Δ to give the azimuth- and elevation- error signals.

5.0 Amplitude- comparison and Phase- comparison monopulse

5.1 Physical construction

In a reflector or lens antenna, the physical distinction is obvious: In amplitude-comparison there is a single main reflector or lens with a cluster of feed horns.
In phase- comparison there is a cluster of four reflectors or lenses side by side in a square or cloverleaf arrangement, jointed together at their edges to form a rigid assembly, each reflector or lens having a single feed horn.
A corresponding method used in some array antennas is to divide the array into four quadrants, collect the contributions of the elements in each quadrant, and process the resulting signals in the same way.

5.2 Antenna patterns

Amplitude- comparison and phase- comparison antenna patterns are distinctive. Figure 5.2.1 illustrates a pair of beams of each class, for one angular coordinate.

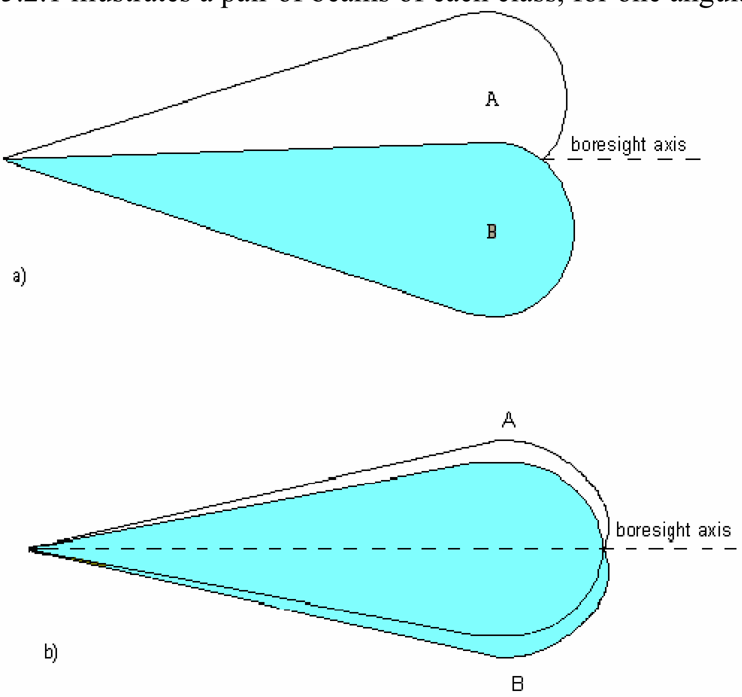


Figure 5.2.1: Monopulse beams, shown in one coordinate:

a) Amplitude- comparison.

b) Phase- comparison.

In amplitude- comparison, the beams have a common phase center, but are squinted symmetrically away from the axis. A target produces voltages of the same phase but different amplitudes in the two beams; the amplitudes are equal only when the target is on the axis.

In phase- comparison the beams are parallel and identical, except for a lateral displacement of their phase centers on opposite sides of the axis. A target produces voltages of the same amplitude but different phases in the two beams, because the path lengths from the target to the two phase centers are different; the phases are equal only when the target is on axis.

5.3 Relative Phase of Sum and Difference

There is no direct comparison of amplitudes of signals from the individual antenna feeds in amplitude- comparison monopulse; instead the comparison is done indirectly by means of the sum and difference. Similarly, in phase- comparison there is usually no direct comparison of phases, but the desired information is obtained by processing the sum and the difference.

In Figure 5.3.1 phasors *v1* and *v2* represent the voltages from two squinted beams (or two pairs of squinted beams) in amplitude- comparison monopulse. Since they are in phase with each other, their sum and their difference are also in phase with each other, as the phasor diagram shows.

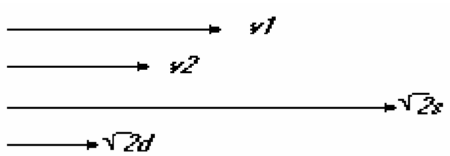


Figure 5.3.1: Phase relationships in amplitude- comparison monopulse.

The in- phase relationship is the idealized or normal condition, which in practice is disturbed to some degree by noise, unresolved targets, system imperfections and other factors.

In figure 5.3.2 phasors *v1* and *v2* represent the voltages from the two beams (or two pairs of beams) in phase- comparison monopulse. They have the same amplitude but different phases, assuming that the target is off- axis. From the geometrical construction it is seen that the *s* and *d* phasors are perpendicular to each other, which means that the sum and difference signals differ in phase by 90º. As in the case of amplitude- comparison, this phase relationship represents the nominal condition, which is subject to various disturbing factors.

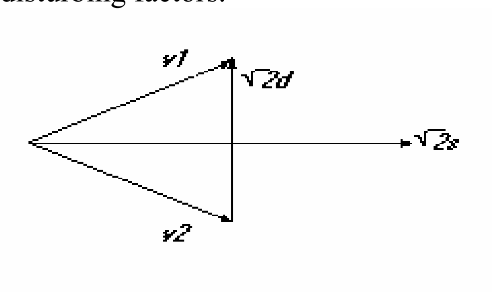


Figure 5.3.2: Phase relationships in phase- comparison monopulse.

5.4 Antenna- feed techniques

Antenna- feed techniques for amplitude- and phase- comparison monopulse systems are different. Antenna- feed for an amplitude comparison system can have a large variety of configurations. Comparator network described above, Figure 3.1.1, can be an example of one of them.
In phase- comparison monopulse system received signal goes directly to the receiver, without any additional passive circuitry. But in order to achieve greater boresight stability these two techniques can be combined and comparator network can be used in phase- comparison monopulse system. The only difference remaining will be a 90° phase shifter on difference signals channels.

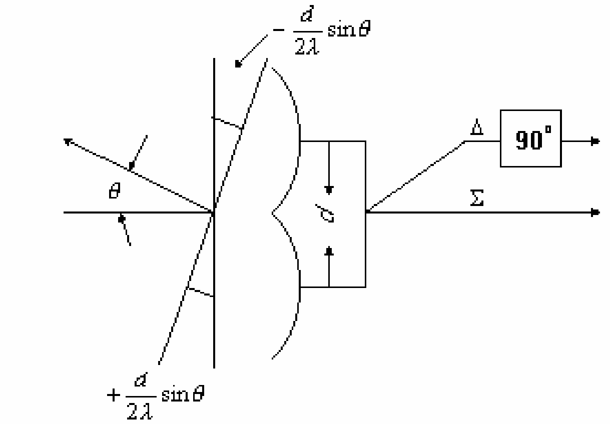


Figure 5.4.1: Phase- comparison monopulse system with sum and difference outputs.

6.0 Monopulse Processor/Detector

6.1 Components in the monopulse processor

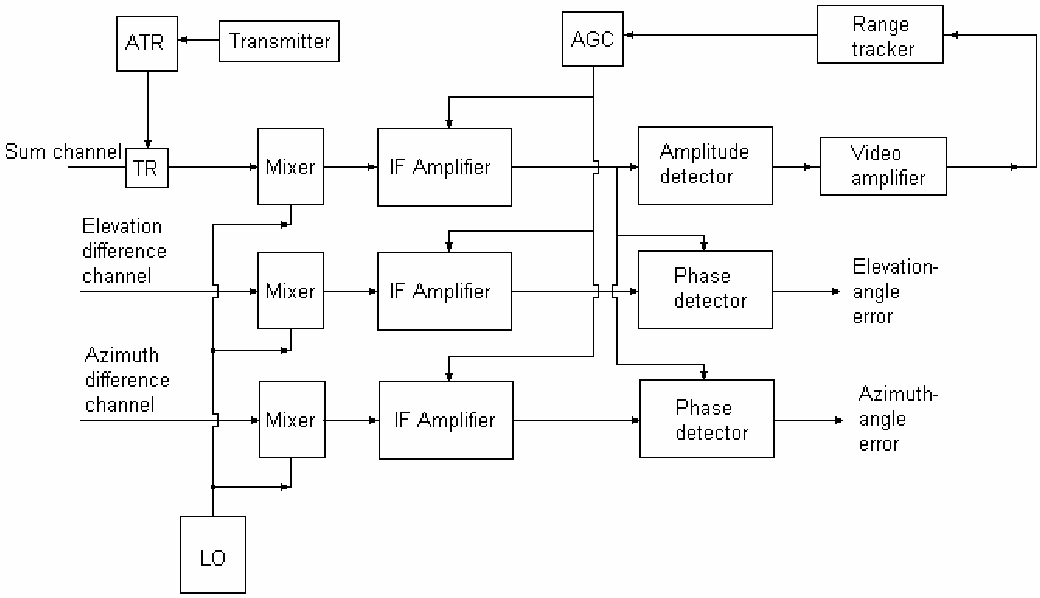


Figure 6.1.1: Block diagram of a monopulse processor.

The sum signal, elevation difference signal and azimuth difference signal are each converted to intermediate frequency (IF), using a common local oscillator to maintain relative phase at IF. The IF sum- signal output is detected and provides the video input to the range tracker. The range tracker determines the time of arrival of the desired target signal and provides gate pulses, which turn on portions of the radar receiver only during the brief period when the desired signal is expected. The gated video is used to generate the dc voltage proportional to the magnitude of the Σ signal or |Σ| for the AGC of all three IF amplifier channels. The AGC maintains constant angle tracking sensitivity (volts per degree error) even though the signal from target varies over a large dynamic range by controlling gain or dividing by |Σ|. AGC is necessary to keep the gain of the angle tracking loops constant for stable automatic angle tracking.

The sum signal at the IF output also provides a reference signal to phase detectors, which derive angle tracking error voltages from the difference signals.

6.2 Local Oscillator and Mixers

The only function of the local oscillator and mixers in monopulse detector is conversion of the received signal frequency to the correct intermediate frequency (IF).

No special type of oscillator can be said to be the one most frequently used because there is a great variety of oscillators and the choice of one depends on the monopulse detector type and specifications.

As for mixers, the most widely used type in monopulse systems is a balanced mixer. This mixer is usually chosen because of its capability to modify the spurious effects (generating harmonics of the carrier frequency) by its symmetry.
The two most common forms of balanced mixer configuration are shown by Figure 6.2.1 a) and b).

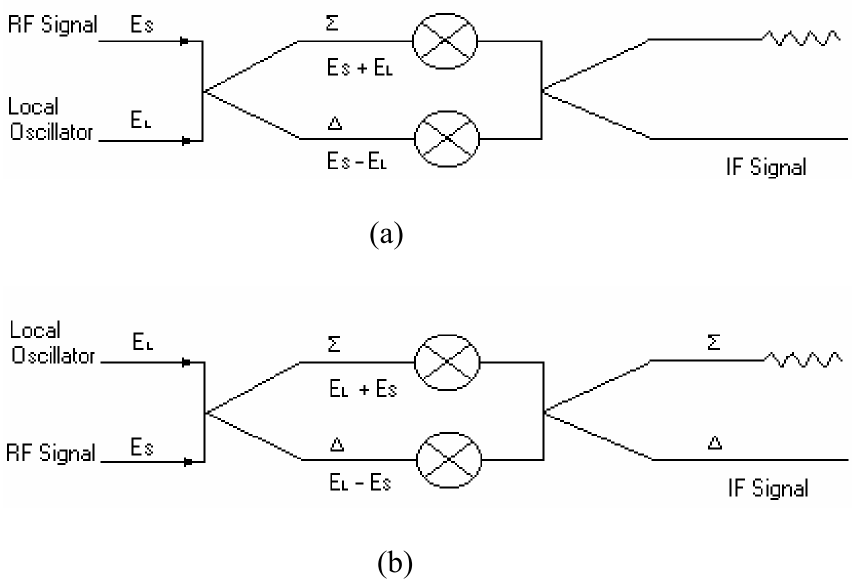


Figure 6.2.1: (a) Balanced mixer with an inverted signal. (b) Balanced mixer with an inverted LO.

The configuration of Figure 6.2.1 (a) suppresses all spurious IF frequencies and spurious RF responses derived from even harmonics of the signal frequency. Also of importance, noise sidebands of the LO which are converted to IF frequency are suppressed at the mixer IF port.

The configuration of Figure 6.2.1 (b) suppresses all spurious IF frequencies and spurious RF responses derived from even harmonics of the LO frequency. Noise sidebands of the LO converted to IF are not rejected by this configuration.

6.3 Automatic Gain Control (AGC) and Gain Controlled Amplifiers

As it has already been mentioned the AGC is necessary to keep the gain of the angle tracking loops constant for stable automatic angle tracking. The problem is that monopulse difference signals from the antenna are proportional both to the angle displacement of the target from the antenna axis and the received signal amplitude. For a given tracking error, the error voltage would change with received signal amplitude and cause a corresponding change in loop gain.

AGC is used to remove the angle- error- detector- output dependence on received signal amplitude and retain constant tracking loop gain.
In a three- channel monopulse detector, all three channels are controlled by the AGC voltage, which effectively performs a division by the magnitude of the sum signal of the received signal amplitude.

From a practical point of view, the most general description of an AGC system is presented on figure X.X. The input signal is amplified by a variable gain amplifier (VGA), whose gain is controlled by an external signal *Vc*. The output from the VGA can be further amplified by a second stage to generate and adequate level of Vo. The detector senses some output signal's parameters, such as amplitude, carrier frequency, index of modulation or frequency; any undesired component is filtered out and the remaining signal is compared with the reference signal. The result of comparison is used to generate the control voltage (*Vc*) and adjust the gain of the VGA.

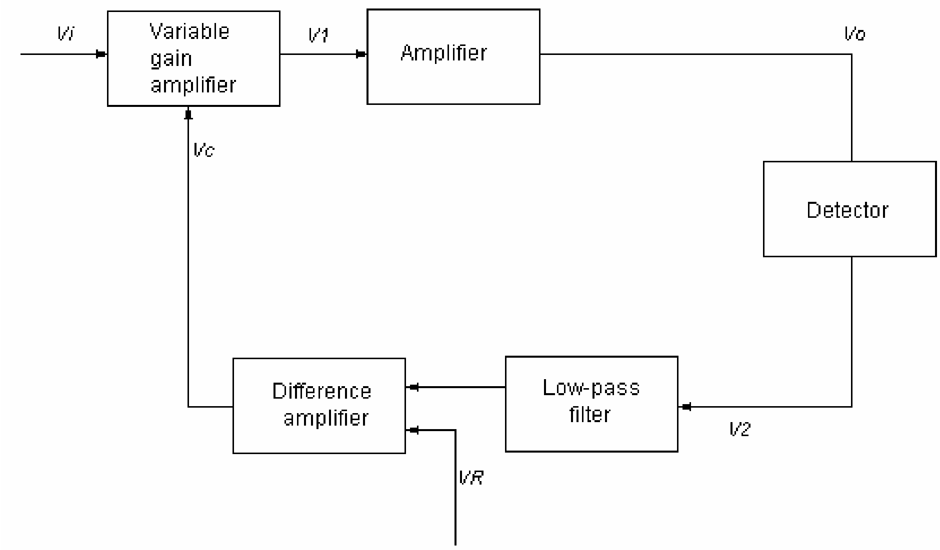


Figure 6.3.1: AGC system.

6.4 Amplitude Detector and Phase Detector

The distinction between a phase sensitive detector and a n amplitude detector is sometimes unclear. This results from the similarity of analog circuits that perform these functions. It is generally agreed, however, that a particular circuit is used as a phase detector when only phase information is present in the output, as an amplitude detector where both phase and amplitude information is present in output.

Balanced- Diode detector, *Coincidence phase detector* and *Analog- to- Digital phase detectors* are examples of the detectors used in monopulse detectors.

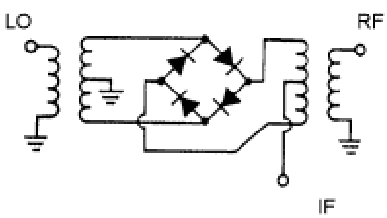


Figure 6.4.1: Balanced- diode detector [29].

Balanced- diode detector of Figure 6.4.1 is most widely used because of its favorable characteristics. When two sinusoids of frequency ω and phase difference θ are applied to this detector, the output is given by

$$Eout = K[(\omega_i - \omega_r)t - (\theta_i - \theta_r)] + K[(\omega_i - \omega_r)t - (\theta_i - \theta_r)] + [higer\_order - terms]$$

(eq 6.4.1)

Under these conditions, the characteristic is sinusoidal, and the ripple is free from a fundamental component. When bandwidth permits, the detector will operate with square-wave inputs to give a triangular characteristic.

6.5 Range Tracker

Range tracker is a part of a monopulse detector used in pulse- type tracking systems. Range tracking is a process of continuously measuring the delay between the transmission of the RF pulse and the echo signal returned from a target. Figure X.X shows an example of a range tracker.

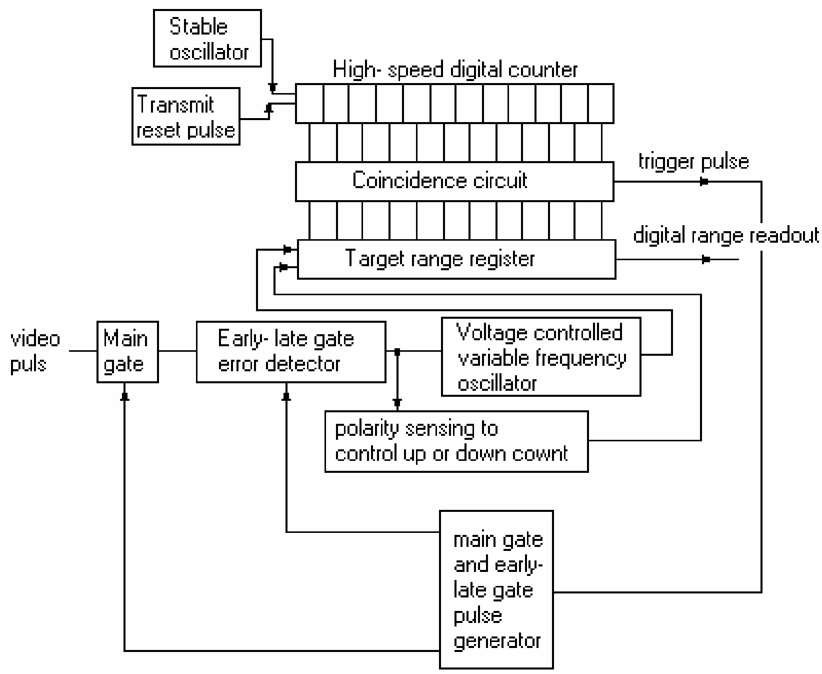


Figure 6.5.1: Block diagram of a digital range tracker.

The block diagram of Figure 6.5.1 shows a digital range tracker that implements a technique that uses a high- speed digital counter driven by a stable oscillator. The counter is reset to zero at the time of the transmit pulse. Target range is represented by number in digital register. A coincidence circuit senses when the digital counter reaches the number in the range register and generates the range gate, as indicated in the block diagram of Figure 6.5.1 A range error sensed by the range- error detector results in an error voltage which drives a voltage- controlled variable frequency oscillator to increase or decrease the count in the range register, depending upon the polarity of error voltage. This changes the number in the range register toward the value corresponding to the range of the target. Range readout is accomplished by reading the number in the range register.

7.0 Possible Errors in Monopulse System Implementation

The basic elements of monopulse are shown in Figure 7.0.1 with two types of error in the electrical elements:

Precomparator error: $d_1 = 1 + a_1 + j\phi_1$ **(eq 7.0.1)**

Postcomparator error: $d_2 = 1 + a_2 + j\phi_2$ **(eq 7.0.2)**

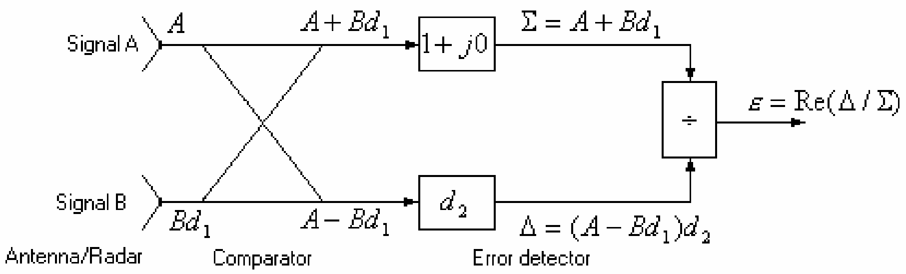


Figure 7.0.1: Monopulse implementation errors.

The imbalance errors for amplitude, a_1 and a_2, are assumed small with respect to unity, and phase imbalance errors φ_1 and φ_2 are small with respect to one radian. Precomparator error is associated with RF components, and is often stated as a null depth *Gn* in the *Δ* pattern, relative to the *Σ* pattern maximum:

$Gn = 4/\phi_1^2$ **(eq 7.0.3)**

Taking into consideration only the first- and second- order terms, we may write the shift in null position, relative to the ideal (error- free) system in terms of an error voltage:

$$E_\Delta(0) = \mathrm{Re}(\Delta/\Sigma)_0 = \\ = (-a_1/2) - (a_1 a_2/2) + (a_1^2/4) + (\phi_1\phi_2/2) - (\phi_1^2/4)$$ **(eq 7.0.4)**

The normalized difference slope, which relates this voltage to angle, is

$k_m = (\theta_3/\Sigma)d\Delta/d\theta$ **(eq 7.0.5)**

Thus, an error voltage E_Δ is equivalent to an angle $\Delta\theta = E_\Delta\theta_3/k_m$, and (eq 7.0.4) may be converted to an angle with this scale factor.
The monopulse network error will also effect the difference slope, changing the error-free value k_m to a value k_m' such that

$k_m'/k_m = 1 + a_2 + (a_1^2/4) - (\phi_1\phi_2) - (3\phi_1^2/4)$ **(eq 7.0.6)**

(retaining only the first- and second- order terms).

In practice, a major portion of the precomparator error is eliminated by offsetting the feed or data system to center the RF null of the system. This displaces the zero point by the amount:

$E_0 = (a_1/2) - (a_1^2/4) - (\phi_1^2/4)$ **(eq 7.0.7)**

Assuming that the precomparator errors remain fixed, the introduction of postcomparator errors (usually associated with gain and phase variations in active elements in the system) will now cause an error signal:

$E_2 = E_\Delta(0) - E_0 = \phi_1\phi_2/2$ **(eq 7.0.8)**

The corresponding angle error for this case is:

$(\Delta\theta)_2 = \theta_3\phi_1\phi_2/2k_m = \theta_3\phi_2/k_m\sqrt{Gn}$ **(eq 7.0.9)**

The rms error σ_θ caused by postcomparator error after setting the RF null to zero is found from (eq 7.0.9) by inserting the rms value of φ_2. This postcomparator phase variation can result from any of the following factors:

- change in the signal power level at the monopulse detector input;
- temperature effects on the monopulse detector components;

In addition, there may be changes in precomparator errors a_1 and φ_1, occurring after calibration and setting to zero. These will cause the null point to shift in accordance with (eq 7.0.4), and can result from any of the following:

- change of operating frequency within the band;
- ambient temperature or solar heating effects on the RF structure;
- polarization changes in the received signal;

It is the active elements in the signal paths that are more likely to increase the gain and phase errors a and φ, as compared to passive elements. Therefore, most monopulse systems place the comparator at RF, as close to the antenna ports as possible.

Active amplifiers in the postcomparator portion of the monopulse detector are essential, and relations (eq 7.0.7) and (eq 7.0.8) can be used to establish the required phase matching φ_2 between Σ and Δ amplifiers.
Another source of error is dc offset in the phase- sensitive detector. This produces a fixed bias error in boresight axis position. To reduce this error, a periodic phase reversal (commutation) is often introduced in the Δ channel, in the RF or early in the IF stages.

8.0 System Development

In this chapter I will introduce three possible solutions for design of a monopulse tracking system.
Some system components are common to all three designs. In order to avoid repetitions I'm going to describe these components before I begin with the description of the designs.

8.0.1 Antenna

Antenna that I suggest to use for the monopulse system is an antenna system/array consisting of 4 x 70 cm, 2x19 element X-Yagi antennas with antenna system gain of around 17-19 dBi. All the antennas are owned by the Norwegian Space Center.

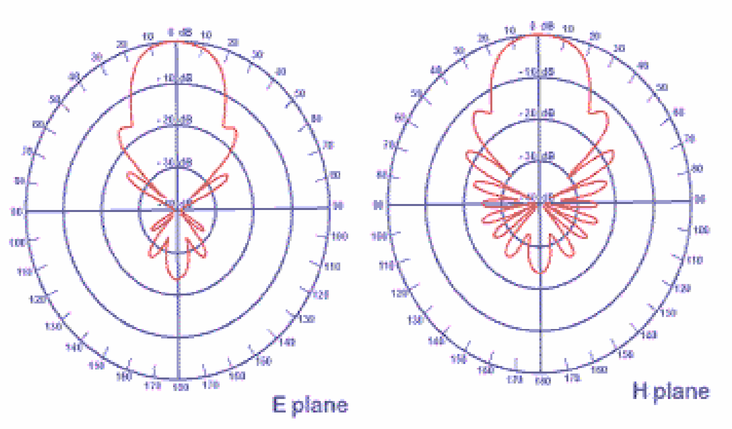


Figure 8.0.1: Radiation pattern of 2x19 elements Yagi antenna.

The principle for the antenna rig is exactly the same as for the downlink antennas of the ground station, [GSEG-03]. Its basis is an H-boom constructed from lightweight aluminium tubing, which carries the four 70 cm antennas.

Antennas are stacked in a quadratic array, spaced 1.25 m (1.8 λ) apart. The complete rig with antennas should be 1.25 m wide, 1.25 m long, and at least 4 m high.

Figure 8.0.2: Antenna rig, [GSEG-03].

8.0.2 Antenna servo system

A possible solution for the servo for the monopulse tracking system can be an azimuth-elevation rotator G-5500 from Yaesu which is owned by Narvik University/College. The azimuth rotator features a turning range of 450°, while the elevation rotator has a rotation range of 180°. This rotator was considered to be too fragile to use for the Ground Station antenna system but the monopulse antenna system consists of only four downlink antennas. It means that antenna rig will be lighter even if there is some extra passive circuitry to be placed on the rig.
The rotator needs two set of cables, both need to be suitable for outdoor use.
For more information and technical characteristics of the rotator see [24] or [GSCOM-02].

Figure 8.0.3: Azimuth- Elevation combination rotator G-5500, Yaesu, [24].

8.0.3 Comparator/Summation network

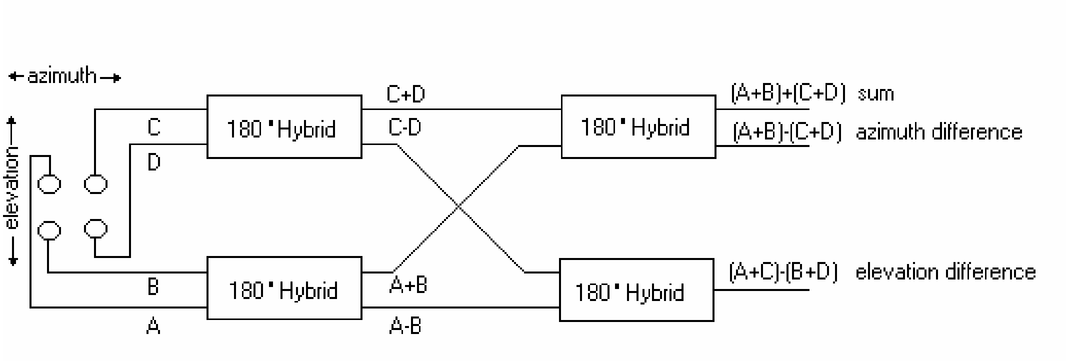
Comparator network can be implemented with the help of four 180° hybrids connected with RG213 type cable, since this cable is more convenient with N-type connectors, and H1000 cable for long span interconnection. The same types of cables where chosen for the connection of the down link antenna system, for more detailed information about the choice of cables and connectors see [GSEG-03] and [GCOM-02].
I was able to find two hybrids that have suitable technical characteristics for use in the comparator network. They are:

Mckdi- Integrated *MH-24N*
Anaren *10013-3*

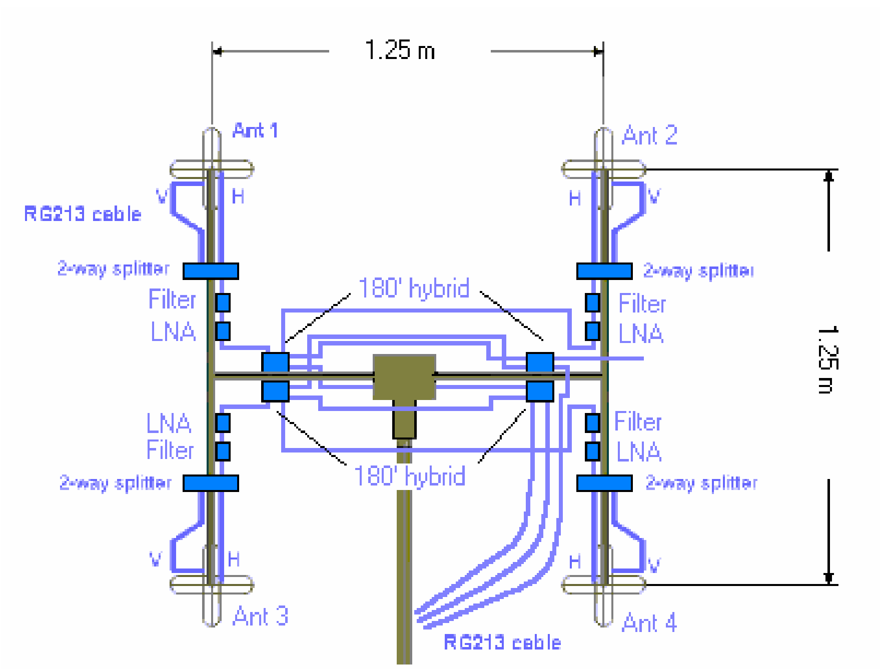
	MH-24N	***10013-3***
Frequency range [GHz]	0.25 - 0.50	0.25 - 0.50
Nominal coupling [dB]	3.0 + 0.25/ -0	3.0 + 0.25/ -0
Maximum insertion loss [dB]	0.300	0.300
Minimum isolation [dB]	20	23
Maximum VSWR	1.30	1.20
Phase balance [Deg]	±2.0	±3.0
Price [$]	29.90	43

Table 8.0.1: Comparison between *MH-24N* and *10013-3*.

Both components have similar characteristics, which are excellent. I recommend using *MH- 24N* – series hybrids from Mcekdi-Integrated because of shorter delivery time and more available price.



a)



b)

Figure 8.0.4: a) Comparator network. b) Cabling for the antenna system and comparator network.

Because of the considerable loss in hybrids and cables, and of course weakness of the received signal, the signal should be amplified. Four LNA's can be placed between the

antennas and hybrids for this purpose, as shown on Fig. 8.0.4. Use of a lightning arrestor should also be considered.
I suggest using the same type of LNA as the one used for the ground station antenna system. Different types of LNA's where evaluated and *DEM 70LNA* from Down East Microwave has been chosen because of its favourable characteristics, [GSEG-03].

The signal should also be filtered to extract noise and unwanted disturbances and to avoid overloading mixers in monopulse detector. A preselector filter of bandpass type can be placed after LNA on each of the antenna channels.

The filter placed between the antenna and the mixer will reject all out- of- band frequencies to prevent them from overloading the mixer. Some spurious responses can be generated in the mixing process. Unwanted interference signals can be translated to the desired intermediate frequency even though they are well separated from the main signal frequency. So that ability of the system to suppress such unwanted interference is dependant upon the filtering preceding the mixer.

I suggest using a 4- pole bandpass filter *DCI-435* from Down East Microwave. This filter can be ordered in a weather proof enclosure and has a suitable narrow passband. The characteristics of this filter are as follows:

Passband	430 to 440 MHz
Passband Loss	typically 1dB
Selectivity	-47 dB at 415 MHz -50 dB at 455 MHz
Power Rating	200 watts
VSWR	1.3:1
Connectors	"N"
Dimensions	12" x 3" x 7.5"
Weight	4 lb. 8 oz.
Price	119 $

Table 8.0.2: General characteristics of *DCI-435* bandpass filter, [20].

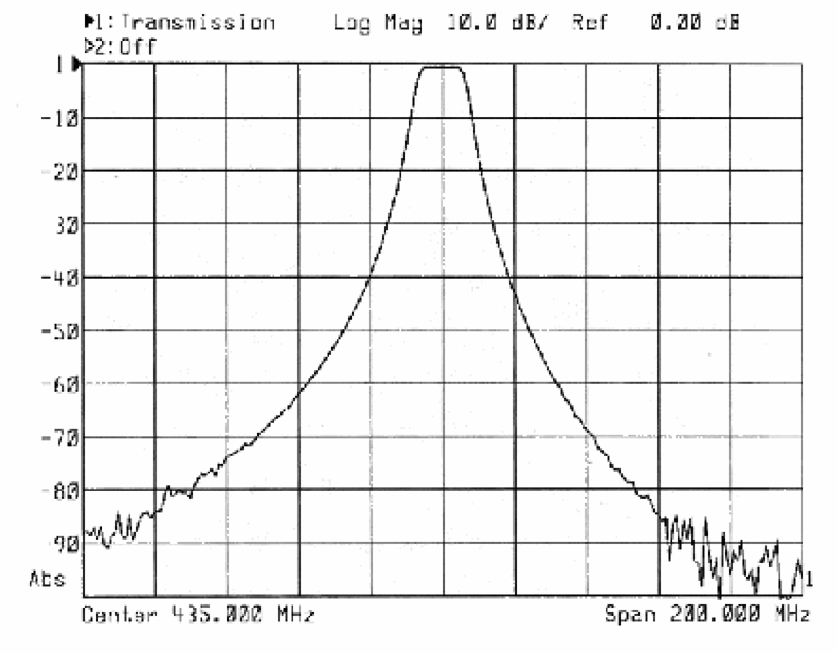


Figure 8.0.5: Network Analyzer frequency response plot for DCI-435 bandpass filter, [20].

8.0.4 Hardware Suggested for Comparator Network

Make & model	Type	Quantity	Unit cost
Mcekdi-integrated *MH- 24N*	hybrid (0/180˚)	4	29.90 $
Tonna *30270*	2- way power splitter (435 MHz)	4	45 $
Down East Microwave *DEM 70LNA*	LNA	4	65 $
Down East Microwave *DCI-435*	Band pass filter	4	119 $
Total Cost			***1035.6 $***

Table 8.0.3: List of hardware needed for the comparator network.

8.1 Design 1, using down converters and monopulse processor

This design of a monopulse tracking system is the easiest one to implement, but at the same time the most expensive one.

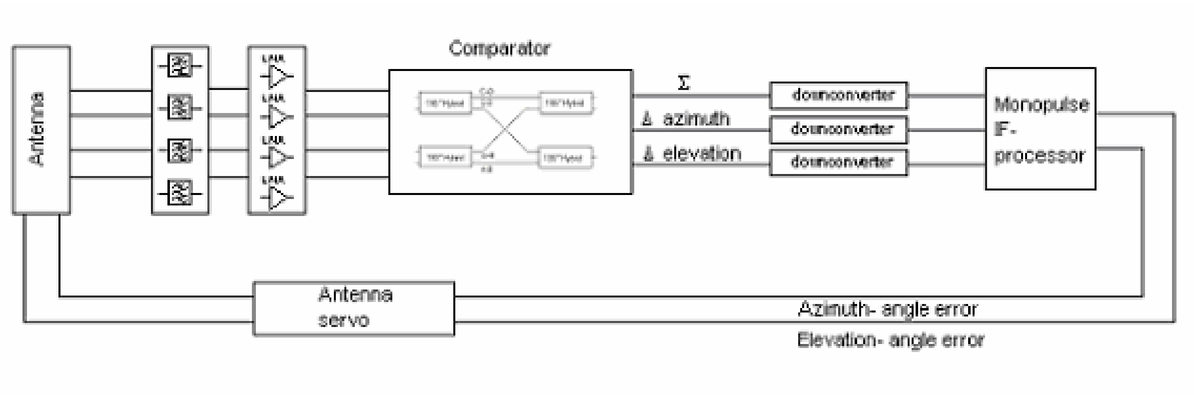


Figure 8.1.1: Block diagram of the 1st design.

Antenna system, comparator network and antenna servo are as described above.

When it comes to the monopulse processor, the only available monopulse detectors/processors on the market at the time of the project where a monopulse IF processor *RTM- 3010* from Radar Technology and a monopulse detector *MMDQ-3010-65* from Miteq. Both devices have excellent characteristics, even too good for our system, but the prices of both of them are very high. These monopulse detectors/processors are developed for use in complex and expensive systems for tracking of objects moving with very high speed. I tried to find something more simple in construction but wasn't able to find any better alternatives.

Characteristics	*RTM-3010*	*MMDQ-3010-65*
Operating frequency	30 MHz	30 MHz
-3dB bandwidth	10 MHz	10 MHz
Phase relationship Σ to Δ	0° or 90°	0° or 180°
Output voltage	+/- 150 mV	+/-2 V
Output rise time	70 nS	0.1µs
Output characteristic	$e_{out} = K\cos((\tan^{-1}\Delta/\Sigma) - 90^{\circ})$	$e_{out} = \frac{1.4(\Delta/\Sigma)\cos\theta}{[11 + 2(\Delta/\Sigma)\sin\theta + (\Delta/\Sigma)^2]^{1/2}}$
Power supply	+/- 15 Vdc, 600mA	+/- 12 Vdc, 500 mA
Price ($)	4345	~ 8450

Table 8.1.1: Comparison between monopulse detectors/processors *RTM-3010* and *MMDQ-3010-65*.

The monopulse detector/processor I suggest to use is the monopulse IF processor from Radar Technology. The main reason why I have chosen this one is that it costs much less than the monopulse detector from Miteq and it can be supplied for either amplitude or phase sensing antenna systems. It means that the processor is designed for phase relationship between the input signals like 0 º, as well as for 90 º, depending on the type of the antenna system.

Since the antenna system I have been thinking to use is of phase sensing type, 90 º-phase relationships should be specified in time of ordering of the monopulse IF processor.

Operating frequency of RTM- 3010 is 30 MHz, which means that sum and difference signals coming from the comparator network should be converted down from 435 MHz to 30 MHz. This down conversion can be done with the help of a receive converter for each channel, as long as all three of them have the same transfer function.

I suggest to use receive converters of *432-28RX*- series from Down East Microwave. An alternative and cheaper solution is to use receive converters of *CC432*-3 series from Hamtronics.
For the best system performance the receive converters should be mounted on the antenna rig as close to the antennas as possible. Because of that, they should be robust and have a weather proof enclosure.

Though the converters from Hamtronics have almost the same characteristics as the ones from Down East Microwave and are much cheaper, they are not available in the weather proof enclosure. That is why I suggest using receive converters from Down East Microwave.

Characteristics	**Hamtronics *CC432-3***	**Down East Microwave *432-28RX***
Noise figure	1-2 dB	1dB
Gain	20 dB	20 dB
Power	+13.6 Vdc, 3040mA	From +11 to +17 Vdc, 400 mA
RF range	435- 437 MHz	432-435 MHz
Output range	28- 30 MHz	28- 30 MHz
Price ($)	99	≈175 (est.)

Table 8.1.2: Comparison between receive converters *CC432-3* and *432-28RX*.

The monopulse IF processor RTM- 3010 measures amplitudes of the sum and azimuth- and elevation difference voltages and their phases relative to a common reference (the phases of the difference signals relative to the phase of the sum signal) and computes outputs having following characteristics:

$$e_{out} = K\cos((\tan^{-1}\Delta/\Sigma) - 90^{\circ}) \qquad \textbf{(eq 8.1.1)}$$

Where:

e_{out} - instantaneous output voltage
Δ/Σ - ratio of Δ input voltage to Σ input voltage

These analog output error- signals can

a) be transformed into control signals for the antenna servo system.

b) with the help of some hardware (A/D converters, filters, amplifiers etc.) be converted to digital and sent to the computer where they can be transformed into degrees in azimuth and elevation and become input data for a tracking program.

8.1.1 Hardware suggested for design 1

Make & model	**Type**	**Quantity**	**Unit cost**
Down East Microwave *432-28RX*	Receive converter	3	175 $
Radar Technology *RTM-3010*	Monopulse IF processor	1	4345$
Total Cost			***4870 $***

Table 8.1.3: Hardware recommended for the 1st design.

8.2.0 Design 2, using a simplified monopulse detector

This design is very much alike the previous one, the major difference is that here I tried to substitute the monopulse detector with a more simple circuit. In this case there will be no need to convert down the sum and difference signals coming from the comparator network. The main idea of this design is shown on Figure 8.2.1.

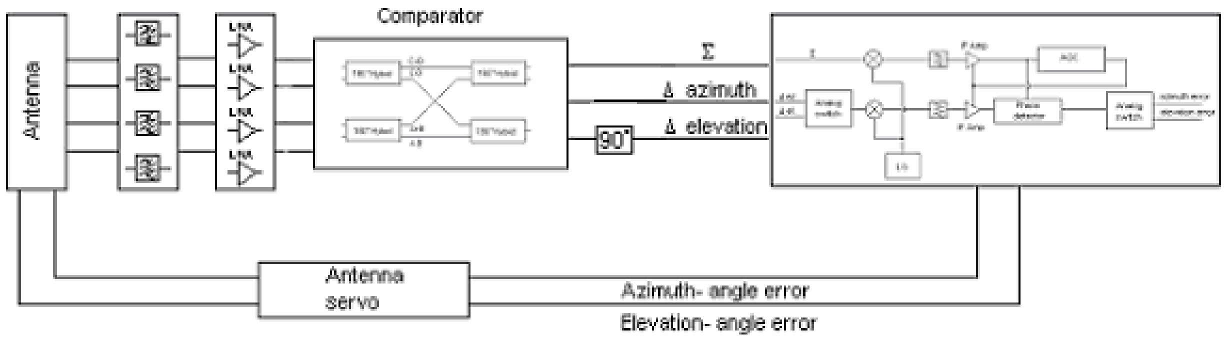


Figure 8.2.1: Block diagram of the 2nd design of monopulse tracking system.

A 90° phase shifter should be placed between the comparator and monopulse detector on the elevation channel so that the system will function as a phase- comparison system. Alternatively, a 90° phase shifter can be placed after the switch on azimuth/elevation channel and be a part of the monopulse detector. I prefer the second alternative because it will be too expensive to buy a connectorized component.
The only suitable phase shifter I was able to find is 90° *B4QF* phase shifter from a Japanese company Toko, but I don't think that it will be any problem to get this component because Toko has sales offices in most European countries.

Building three receiver chains to achieve the monopulse detection function, has a large impact on the size and most important on the cost of the system. Fortunately, in our case, the error signals will typically vary rather slowly in time. In this situation it is possible to combine the two error signals such as the monopulse detector can perform its function using only two receiver chains. The resulting system is much less complex and costly than the system shown on Figure 6.1.1. In addition to one receiver chain, the need for multiple AGC loops and one phase sensitive detector can be removed.

An analog switch can switch between the two difference signals (azimuth and elevation difference signals) coming from the comparator network.

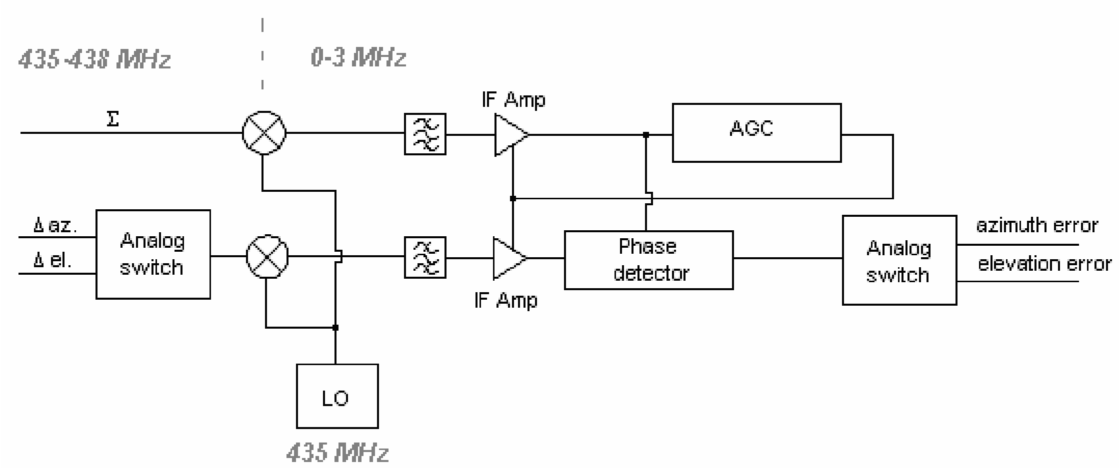


Figure 8.2.2: Monopulse detector with two receiver chains.

Since the signals recovered from the monopulse detector are used to drive mechanical servos, a fairly low modulation frequency can be used.

During the transition time between one difference signal to another the switch cannot be used. The *Δaz* and *Δe*l will be degraded but I think that that is not a concern in our case.

The sum and the difference signals (switched azimuth and elevation difference signals) are converted to intermediate frequency IF using a common local oscillator to maintain relative phase at IF. To maintain constant angle sensitivity the sum signal is fed into the automatic gain control.

When two input voltages e_1 and e_2 are applied to a multiplying device, it produces an output $|e_1| \cdot |e_2| \cos\delta$, where δ is the relative phase between the two input voltages. It is called a *dot- product detector* because of the analogy with the dot- product (scalar product) operation in vector algebra.

If the sum and difference voltages (now we have only one channel for azimuth and elevation differences) were used as inputs, the output would be $|s| \cdot |d| \cos\delta$. In order to convert this to the desired output expressed by equation **X.X**, it is necessary to divide by $|s|^2$. This can be done by dividing *s* and *d* by |s| before those voltages are applied to the phase/dot- product detector. The division can be accomplished by automatic gain control

(AGC) derived from the sum channel and controlling both the sum and the difference channels. The AGC keeps the sum voltage at a constant voltage while the phase is preserved. Thus the sum voltage after AGC will be s/|s| and the difference voltage after AGC will be d/|s|.

A practical AGC system is shown on figure XX. Maximum operating frequency of this circuit is 80 MHz. This circuit is included in the demo board of the OPA660 of Burr Brown (which is now a part of Texas Instruments). The OPA660 is a high bandwidth, high slew rate Operational Transconductance Amplifier whose transconductance can be varied by means of a resistor connected to pin 1.

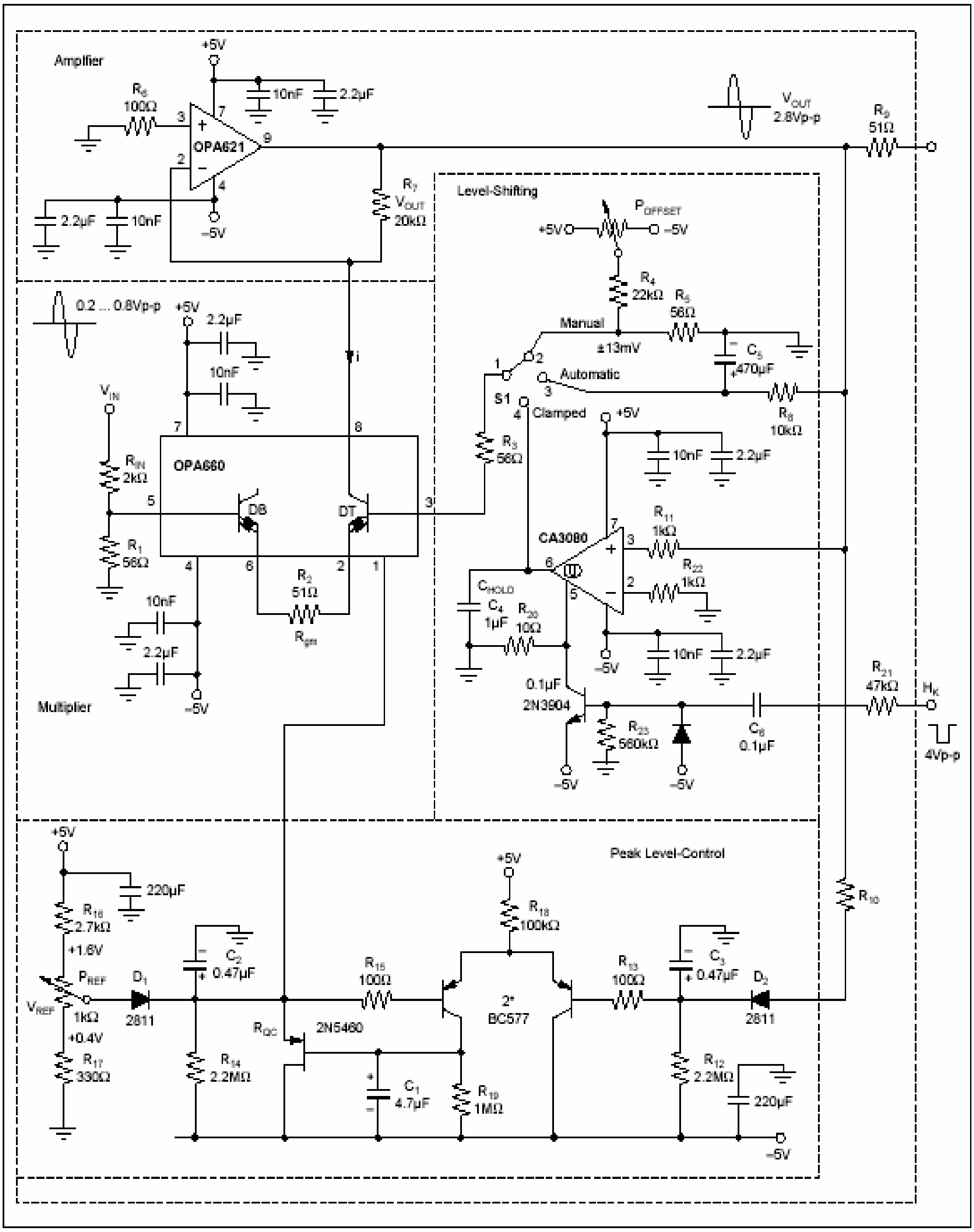


Figure 8.2.3: AGC system, [25].

In this circuit, the input signal, coming from the sum channel, is attenuated by the resistive divider at the input of the OPA660 and converted into a current I_{OUT}. The output current is converted back into a voltage by the second amplifier OPA621. The peak value of the output voltage is checked against the reference voltage V_{REF} by the discrete differential amplifier. The error voltage is multiplied by the gain of the discrete differential amplifier, applied to the gate of the JFET 2N5460 and filtered by the RC network (R_{19} and C_1).
The output transconductance of the JFET adjusts the quiescent current at pin 1, thus, changing the trunsconductance of the OP660 and modifying the total gain of the circuit. The process continues until the system reaches the steady state. The gain of the IF amplifier is being adjusted by the output voltage V_{OUT}.

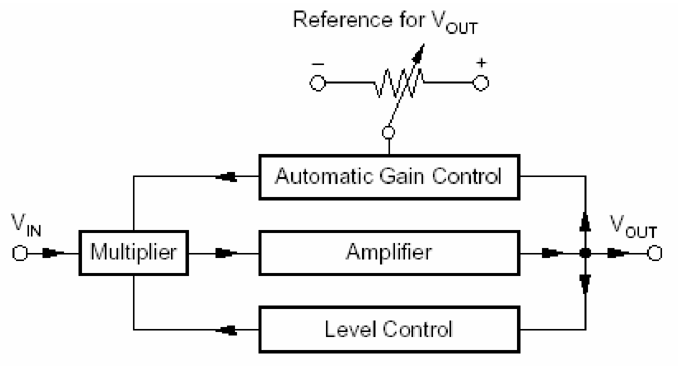


Figure 8.2.4: AGC schematic, [25].

The final part in this monopulse detector circuit is a phase sensitive detector. I suggest using a double balanced mixer as a phase detector.

The mixer equation:

$$Eout = K[(\omega_i - \omega_r)t - (\theta_i - \theta_r)] + K[(\omega_i - \omega_r)t - (\theta_i - \theta_r)] + [higer\_order - terms]$$

(eq 8.2.1)

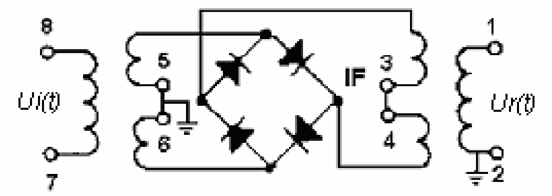


Figure 8.2.5: Phase detector schematic.

In our case *Ui(t)* is the difference signal coming from the IF difference channel amplifier, and the reference signal (here *Ur(t)*) is the sum signal fed from the IF sum channel amplifier. *Ui(t)* and *Ur(t)* signals are of the same frequency.

In a phase detector application the terms $\omega_i = \omega_r$, therefore the first term $\omega_i - \omega_r = 0$, and the output of the detector is only a function of

$$Eout = K(\omega_r - \omega_i) + K\cos(2\omega t) + higer\_order\_terms$$ **(eq 8.2.2)**

With proper filtering, the $2\omega t$ terms and higher order terms can be eliminated, so the output is equal to $Eout = K\cos\theta_e$

Where K is the phase detector gain (dependent on the amplitude of the input signals) and

$$\theta_e = \theta_r - \theta_i$$

is the phase error.

To be quit the unwanted components at the phase detector output the error signal coming out should be filtered and amplified because the expected error signal amplitude will be too small (measured in mV).
A following RC combination which will act as a low pass-filter to attenuate the sum frequencies can be used. If additional filtering is required, a multiple-section RC filter can be used.

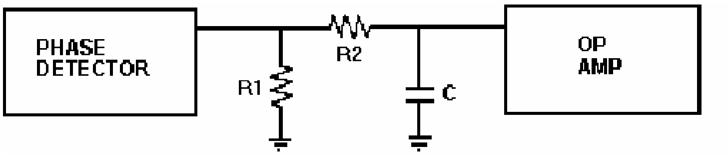


Figure 8.2.6: Filtering the phase detector output.

An alternative and simpler solution is to use the same low pass filter (*PLP-2.5)* as for the down conversion stage.

The error signal on the output of the operational amplifier following the phase detector is switched between azimuth and elevation channels, so that both error signals (azimuth and elevation error signals) can be generated.

Both signals will be of the form $Eout = K \cdot \cos\theta_e$ where phase detector gain $K = \frac{\hat{U}_i \cdot \hat{U}_r}{2}$, *Ui* and *Ur* are amplitudes of the incoming signals, and *θ* is the phase difference.

As in the previous design the azimuth and elevation error signals coming from the monopulse detector can be

c) transformed into control signals for the antenna servo system.

d) with the help of some hardware (A/D converters, filters, amplifiers etc.) converted to digital and sent to the computer where they can be transformed into degrees in azimuth and elevation and become input data for a tracking program.

8.2.1 Hardware suggested for design 2

Make & Model	Type	Quantity	Unit cost
Analog devices *ADG 411*	Analog Switch	2	11.95 $
Mini-circuits *ASK-1-KK81*	Mixer	2	6.95 $
Mini-circuits *JTOS-535*	VCO	1	15.95 $
Mini-circuits *PLP-2.5*	Low Pass Filter	4	14.95 $
Motorola *MC1350*	Monolithic IF Amplifier	2	19.90 $
Mini-circuits *MPD-1*	Phase detector	1	21.45 $
Toko *B4QF*	90° Phase shifter	1	30 $ (est.)
Total cost			***204.8 $***

Table 8.2.1: Hardware recommended for monopulse detector (for hardware for AGC see table 8.2.2 bellow).

Designation	Part Name	Quantity	Unit cost
IC1	OPA621KP	1	2.93 $ (est.)
IC2	CA3080	1	2.25 $ (est.)
IC3	OPA660AP	1	4.57 $ (est.)
T1, T2	BC577	2	3.95 $ (est.)
T3	2N5460	1	1.53 $ (est.)
T4	2N3904	1	1.87 $ (est.)
D1, D2	2N2811	2	2.25 $ (est.)
D3	1N4148	1	2.45 $ (est.)
R1, R3, R5	56 Ω	3	
RIN	2 kΩ	1	
Rgm	51 Ω	1	
R6, R13, R15	100 Ω	3	
R7	20k Ω	1	
R4	22k Ω	1	
R8, R20	10k Ω	2	
R11, R22	1k Ω	2	
R23	560 kΩ	1	
R21	47 kΩ	1	
R10		1	
R12, R14	2.2M Ω	2	
R18	100k Ω	1	
R17	330 Ω	1	
R16	2.7 kΩ	1	
R19	1M Ω	1	
	Capacitor 2.2 μF	6	
	Capacitor 10 nF	6	
C2, C3	Capacitor 220 μF	2	
C5	Capacitor 0.47 μF	2	
C6	Capacitor 470 μF	1	
C4	Capacitor 0.1 μF	1	
	Capacitor 1μF	1	
Total cost			***28 $ (est.)***

Table 8.2.2: Hardware suggested for implementing AGC, [25].

All components listed in the table above can be obtained from Texas Instruments, but I assume that majority of components, such as resistors and capacitors, can be available at Narvik University/ College.

8.3.0 Design 3, using NI PCI-6014 board

This design is different from the previous two ones. Here, the idea is, because of high price and complexity of monopulse detector/processor, to convert down the sum and the difference signals right after the comparator network. Figure 8.3.1 shows the basic principle of this design.

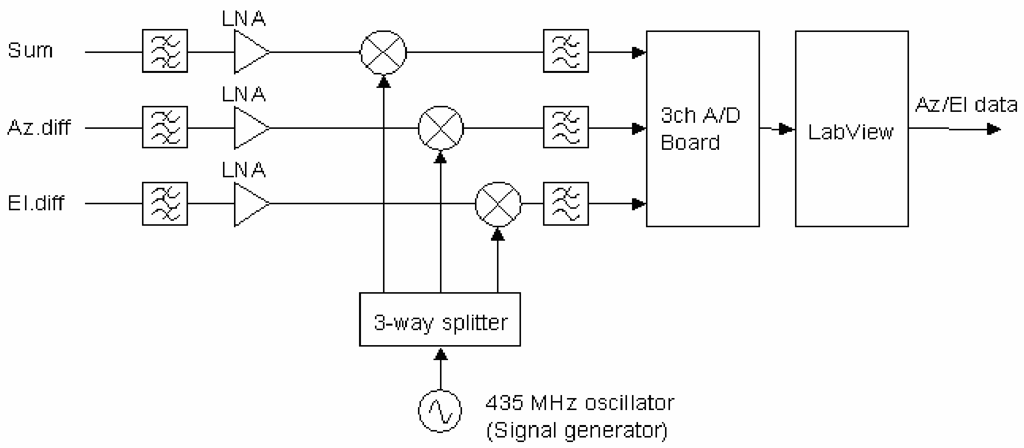


Figure 8.3.1: Diagram of the 3rd design.

Antenna system, comparator network and antenna servo system are exactly the same as described in the beginning of this chapter.

The sum and the difference signals are converted down to intermediate frequency by combination of mixers and signal generator. A 3- way power splitter will be needed to split the generator signal into three channels.

I found two different mixers that could be suitable for this particular design. They are: *X2L-03-411* from Pulsar Microwave and *ZEM-2B* from Mini Circuits.

Characteristics	*X2L-03-411*	*ZEM-2B*
LO/RF [MHz]	0.1- 500	10-1000
IF max. [MHz]	500	1000
Conversion Loss [dB]	7.5	7
LO Drive [dBm]	+7	+7
1db comp.pt. [dBm]	+1	+1
Price [$]	53 $	59.95 $

Table 8.3.1: Comparison between *X2L-03-411* and *ZEM-2B*.

As you can see from the table above both models have almost the same characteristics with the exception of frequency range. Because of more suitable frequency range I recommend using the one from Pulsar Microwave.
A signal generator can be borrowed from one of electro- laboratories at Narvik University/ College.

Output signals from mixers should be filtered to reject all out- of- band frequencies. Since there are no undesired signals between 0 to 3 MHz, a low-pass filter can be used. A bandpass filter can also be used but low-pass filter has half as many reactive components as the bandpass filter. Therefore, it would cost much less than a bandpass filter. I suggest using a low pass filter *NLP-1.9* from Mini Circuits. It has suitable passband and cut- off frequency like 3.0 MHz.

A 3- channel *PCI-6014* A/D board from National Instruments can be used to process information about phase difference between sum and difference signals digitally, using for example LabVIEW. This type of A/D board is used for a broad variety of applications including for example high voltage and sensor measurements. Both driver software (NI-DAQ) and DAQ cable are included.

Model
- NI PCI-6014

- 16 analog inputs at 200 kS/s, 16-bit resolution
- Up to 2 analog outputs, 16-bit resolution
- 8 digital I/O lines (5 V TTL/CMOS) two 24-bit counter/timers
- Digital triggering
- 4 analog input signal ranges
- NI-DAQ driver simplifies configuration and measurements

Operating Systems
- Windows 2000/NT/XP/Me/9x
- Others such as Linux

Recommended Software
- LabVIEW
- LabWindows/CVI
- Measurement Studio for Visual Basic
- VI Logger

Other Compatible Software
- Visual Basic
- C/C++

Driver Software
- NI-DAQ

Table 8.3.2: Characteristics of *NI PCI-6014*, [28].

8.3.1 Hardware Suggested for Design 3

Make & Model	Type	Quantity	Unit cost
National Instruments *NI PCI-6014*	3- channel A/D board	1	515 $ (est.)
Mini Circuits *NLP-1.9*	Low pass filter	3	37.95 $
Pulsar Microwave *X2L-03-411*	Mixer	3	53 $
Pulsar Microwave *P3-02-412*	3- way splitter	1	54.95 $
	Signal Generator (HIN)	1	
Total cost			***842.8 $***

Table 8.3.3: Hardware recommended for the 3rd design.

9.0 System Simulation in MATLAB

Since I wasn't able to test any of the equipment discussed in the previous chapters, because of financial problems and lack of time, I tried to simulate one of the suggested designs in MATLAB.

I have chosen to simulate the second design, described in chapter 8.2, because this design is the one that describes best and in more detail the main idea of the monopulse tracking system.
Because of the complexity of the complete monopulse system I was only able to simulate it without the feedback from the output of the monopulse detector to the antenna system servo. So that the result of the simulation is information about pointing error of the antenna system both in azimuth and elevation given in degrees, but only for one particular position of the target.

There are some moments that I would like to have a closer look at before I start description of simulation.

9.1.0 Filter Design and Simulation

A filter provides a principle means by which the system discriminates between desired signals and interference of many types. Figure 9.1.1 illustrates use of two of the most common filters, preselector and IF filters.

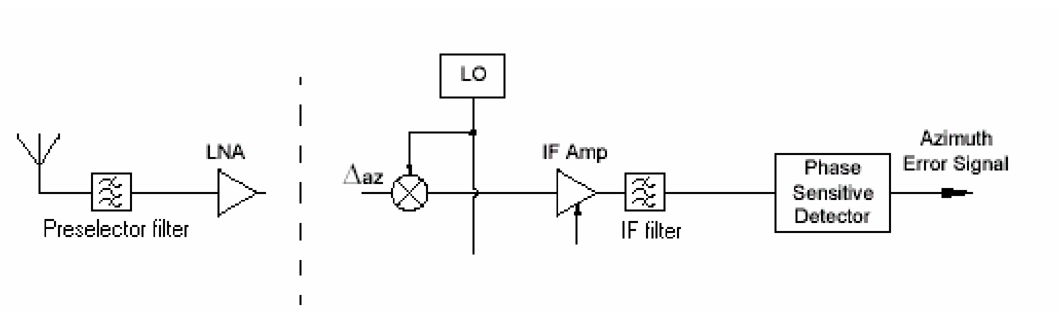


Figure 9.1.1: A fragment from the monopulse system (with comparator network omitted).

Preselector filter

A preselector filter is the filter placed between the antenna and the mixer. It rejects all out-of-band frequencies to prevent them from overloading the mixer. Some spurious responses can be generated in the mixing process. Unwanted interference signals can be translated to the desired intermediate frequency even though they are well separated from the main signal frequency. The ability of the system to suppress such unwanted interference is dependant upon the filtering preceding the mixer, and, of course, on the quality of the mixer itself.

IF filter

An intermediate frequency filter is placed between the mixer and the phase/amplitude detector. Phase/amplitude detector produces a signal that is in some way proportional to the IF signal. Various frequency components of the input noise, which may be far removed from the spectrum of the desired signal, can intermodulate to produce the correct detector output. The consequence of such interference is necessity of predetection filtering.

Since I tried to make the simulation be as close to reality as possible, I have simulated filters of the same order as the ones in the hardware list recommended to use in the second design. I have also simulated both filters frequency responses and calculated the values of components.

9.1.1 Preselector Filter

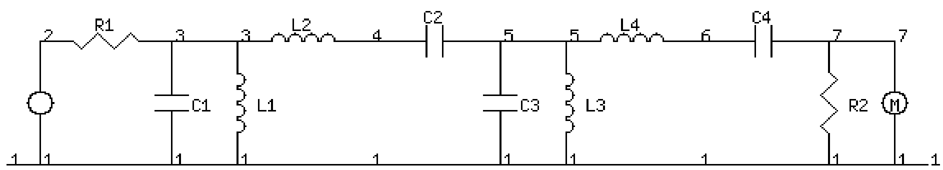


Figure 9.1.2: Circuit diagram for the preselector filter, 4th order bandpass Butterworth.

Components Values	
R1, R2	1000 Ω
C1	4.06057e-11 F
L1	3.27404e-09 H
L2	9.80394e-05 H
C2	1.35604e-15 F
C3	9.80394e-11 F
L3	1.35604e-09 H
L4	4.06057e-05 H
C4	3.27404e-15 F

Table 9.1.1: Component values for the preselector filter.

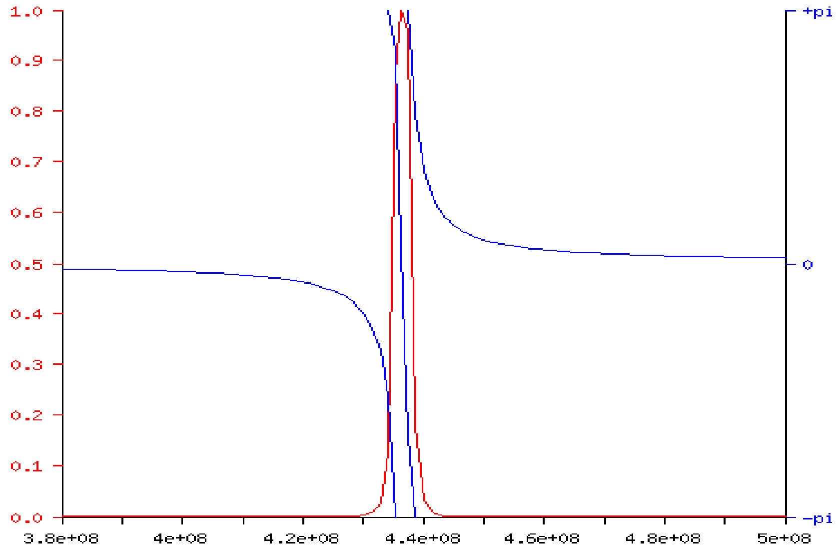


Figure 9.1.3: Frequency response of the preselector filter.

9.1.2 IF Filter

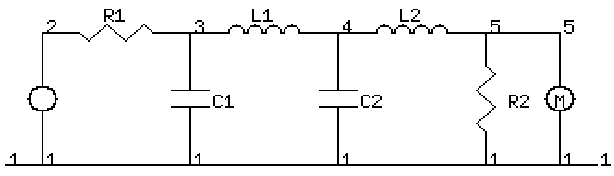


Figure 9.1.4: Circuit diagram for the IF filter, 4th order lowpass Butterworth.

Component Values	
R1, R2	1000 Ω
C1	4.06057e-11 F
L1	9.80394e-05 H
C2	9.80394e-11 F
L2	4.06057e-05 H

Table 9.1.2: Component values for the IF filter.

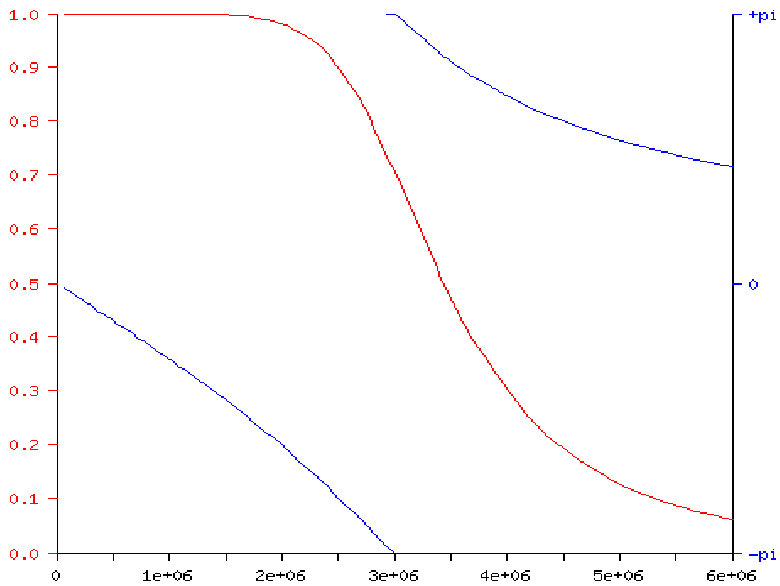


Figure 9.1.5: Frequency response of the IF filter.

Function of both the preselector and the IF filters can be seen from the simulation results in chapter 9.5.0 figures 9.5.3 and 9.5.6.

9.2.0 Signal Delay/ Phase Shift by 90 degrees in MATLAB

A phase shift by 90° can be accomplished both by a continuous time delay and a Hilbert transformer which is a physical system that achieves the necessary 90° retardation of all frequency components.
If a cosine were input to a Hilbert transformer, an output would be sine. And in the opposite, if an input were a cosine, an output would be sine. Both would be true for either a continuous- time or a discrete- time Hilbert transformer.

Achieving a 90º-retardation of all frequency components is different from a constant time delay of all frequency components, and at the same time more difficult to achieve.
I have chosen to use time delay of all frequency components because use of a Hilbert transformer involves digitalization of signal what means that some important information about phase relations between the sum and the difference signals can be lost.

9.3.0 Amplifying

To simulate the system correctly, I had to amplify each of the four "received" signals, as well as amplify the sum, azimuth and elevation difference signals after down conversion and after phase detection stages.

But since it is just a simulation, the main idea of which is to check if the system works and to see how it works, and where simulation blocks do not have any exact losses, I had to make assumptions based on values of real components to decide about how much the signals should be amplified.

9.4.0 AGC

The purpose of the AGC in the monopulse system is to ensure constant loop gain in the error channel, as target signal amplitude changes with range or target fluctuation.

As I have already mentioned above, I have simulated the monopulse system without the feedback from the monopulse detector to the antenna system servo. It means that the simulated system is only capable of detecting the present position of the target, giving the information about how many degrees in azimuth and elevation the antenna should be moved to get the target on its boresight. In this case use of the AGC can be avoided because the target signal amplitude will remain unchanged.

9.5.0 Simulation

As I have already mentioned, I have simulated the monopulse system only for one particular position of the satellite.
Imagine the antenna beam divided into four sectors, with antenna system boresight in the middle, as shown on figure 9.5.1 bellow.

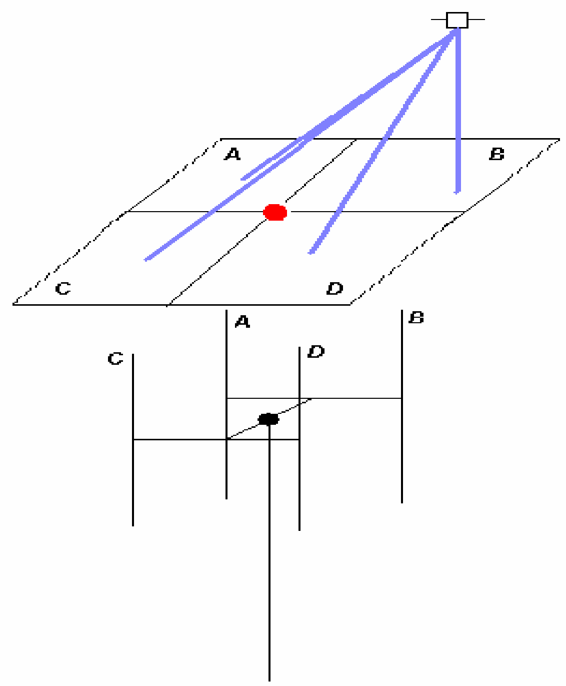


Figure 9.5.1: Division of the antenna beam into 4 sectors A, B, C and D.

In the simulation I assumed that the satellite was somewhere in sector B, so that the signals received by antennas A, C and D will be detected with some time delay in relation to the signal received by antenna B. I have simulated signals A and D with time delay like 1.0e-11*6.39 seconds which is a 10°-delay, and signal D with some longer delay like 1.0e-10*1.277 seconds which is a 20°-delay. Both time delays are pure assumptions because of the unknown conditions in signal transmission and range of the satellite.

So what I expect the system to do is to give me information about for how many degrees I have to move the antenna in azimuth and elevation in order to have the satellite on the antenna system boresight.

9.5.1 Antenna

To make the simulation closer to reality I added white noise to each of the four signals (A, B, C and D) where each signal has frequency like 435 MHz and amplitude like 0.1. All four signals are filtered and amplified before they go into the comparator network. On the figure 9.5.2 bellow, you can see the complete network I built to simulate the monopulse system.

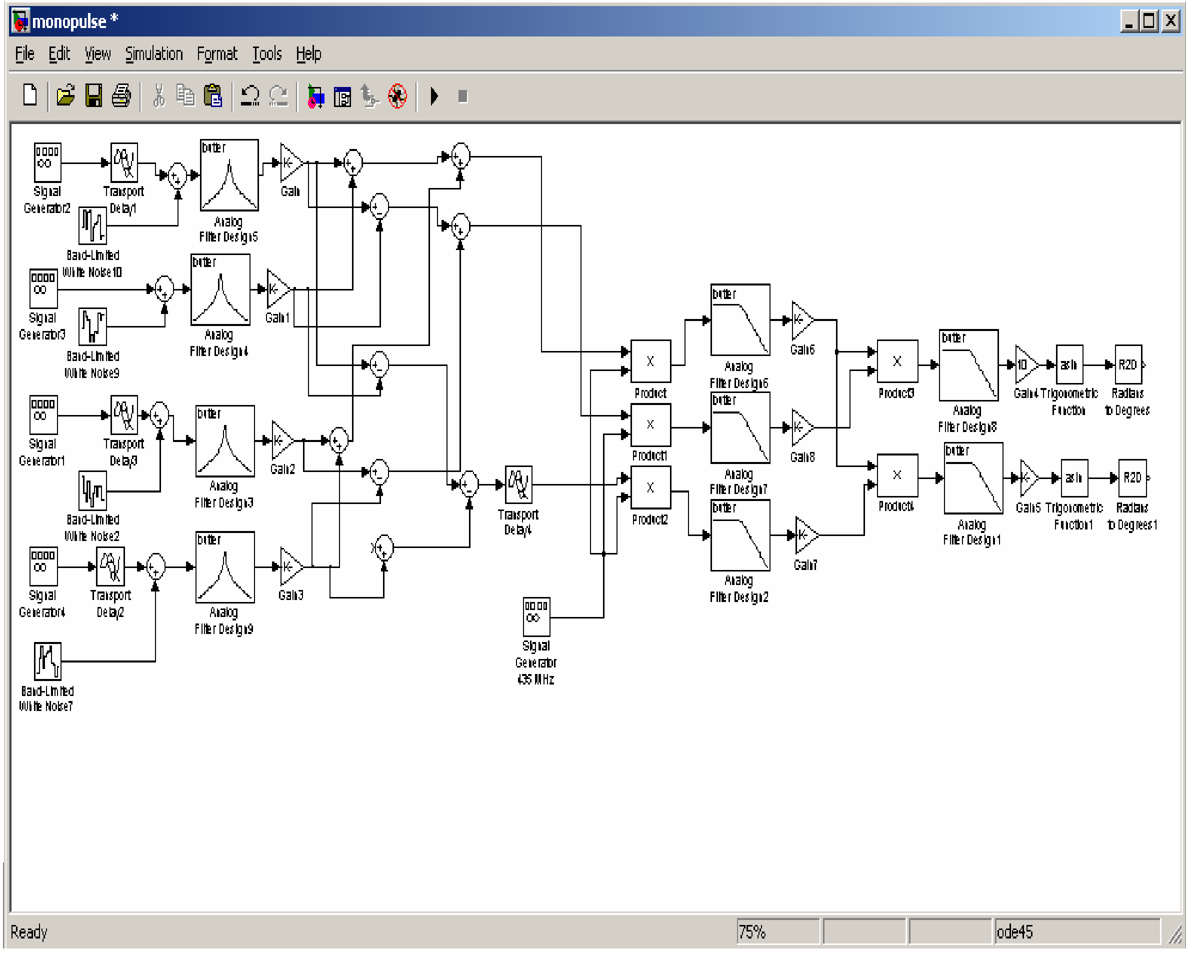


Figure 9.5.2: Phase-comparison monopulse system simulation in Simulink.

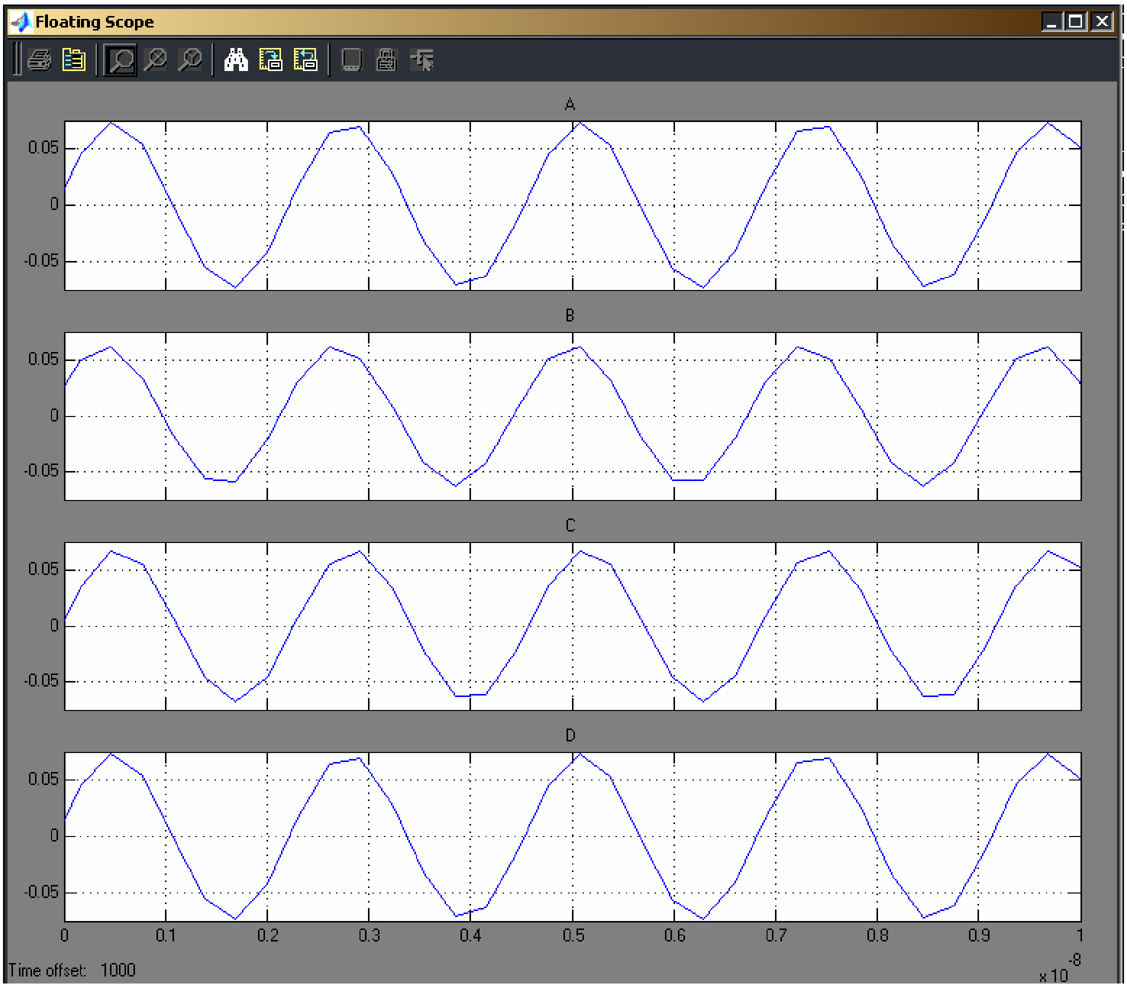


Figure 9.5.3: A, B, C and D signals after preselector filters.

As you can see from the figure 9.5.3 above, the preselector filters work perfect, there is almost no trace of noise or any unwanted interferences, but, of course, it is not a result to be expected in reality.

9.5.2 Comparator network

In the comparator network sum, azimuth and elevation difference signals are formed. To simulate the function of hybrids, which are used in reality, I have used usual sum and difference Simulink blocks as can be seen on the figure 9.5.2 above.

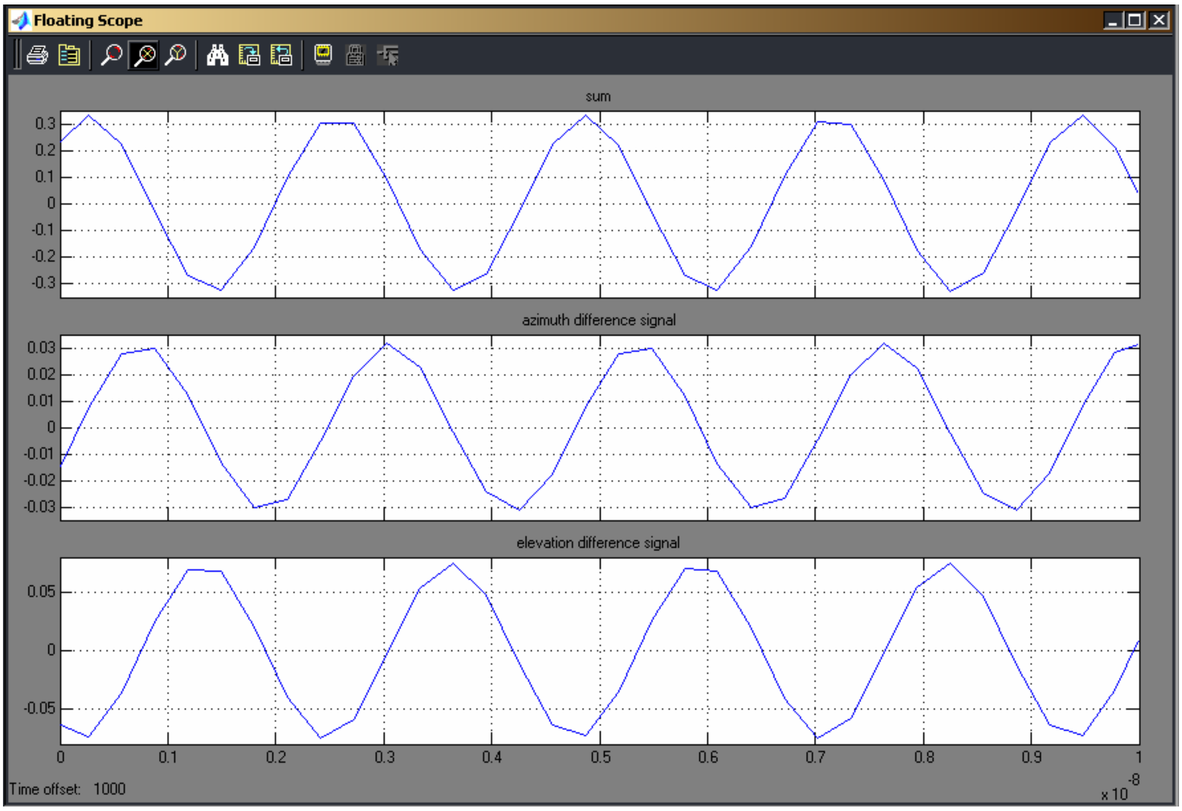


Figure 9.5.4: Sum, azimuth and elevation difference signals after the comparator network.

9.5.4 90°-phase shift

To make the system function as a phase- comparison monopulse system I put a time delay on the elevation channel between the comparator network and mixer. For a frequency like 435 MHz a 90°-phase shift can be represented by a 1.0e-10*5.75 seconds time delay.

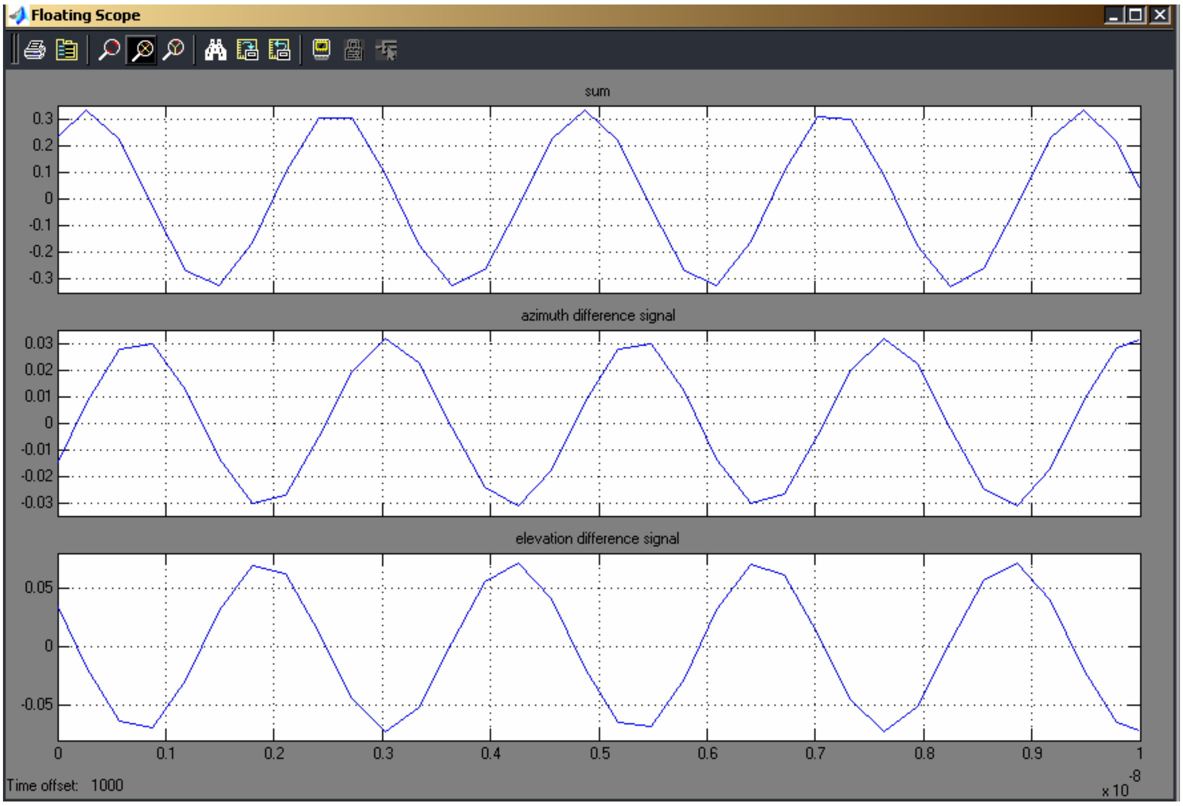


Figure 9.5.5: Sum, azimuth and elevation difference signals after the 90°-phase shift in elevation difference signal.

9.5.5 Down conversion

To simulate the function of a mixer I used a simple cross product block from the Simulink math library. Each mixer is followed by an IF filter and an amplifier. As you can see from the figure 9.5.6 shown bellow, frequency of the sum, azimuth and elevation difference signals has been converted down from 435 MHz to frequencies in 0 – 3MHz bandwidth.

The result of this stage in simulation is almost as I have expected, with the exception of presence of some unwanted frequency components that could be generated from the noise that remained after the preselector filters or as a result of remaining of some unwanted multiplication products of the LO and RF signals.

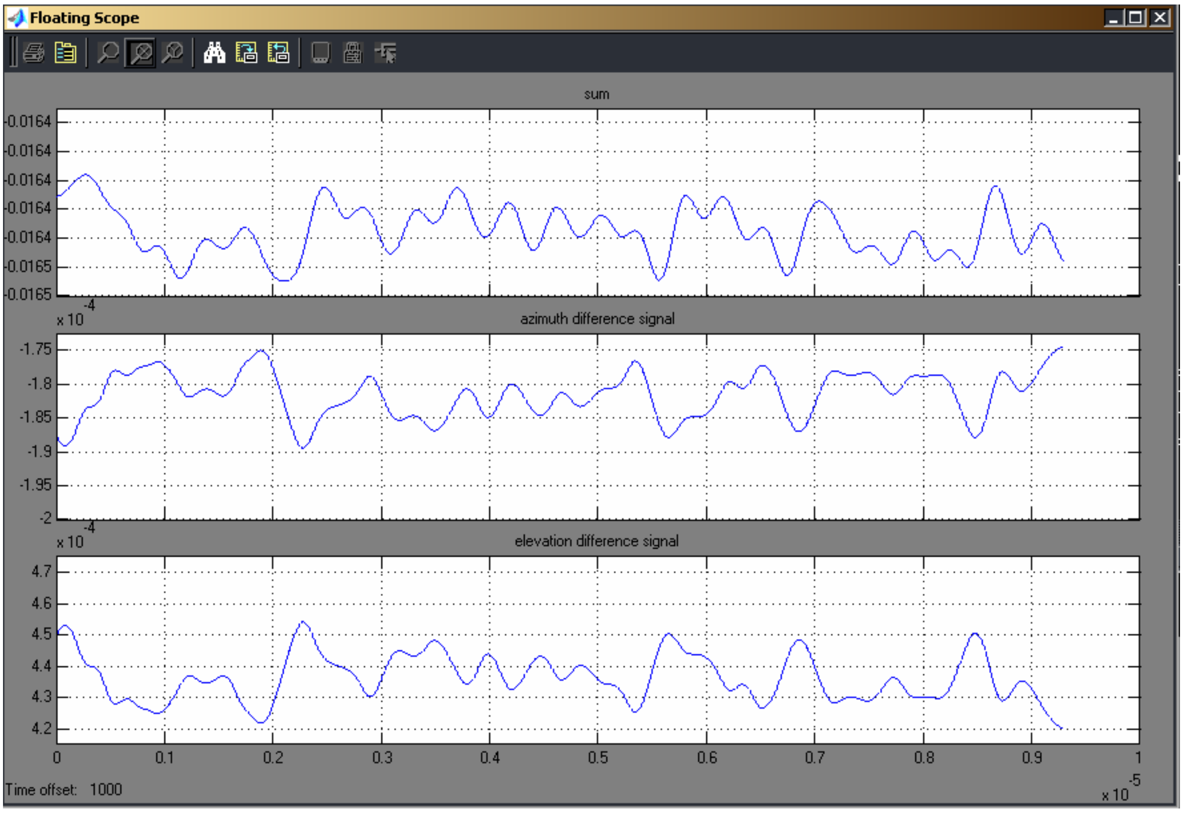


Figure 9.5.6: Sum, azimuth and elevation difference signals after down conversion.

9.5.6 Phase detection

In the 2nd design I suggested to use a double balanced mixer as a phase sensitive detector. To simulate a phase detector I used the same function block as for a mixer (cross product block from the Simulink math library).

The sum signal at the IF output provides a reference signal to phase detectors, which derive angle tracking error voltages from the difference signals. Both azimuth and elevation error signals are filtered and amplified.

Result of this stage in monopulse system simulation is show in the figure X.X bellow.

Both signals are of the form $Eout = K \cdot \cos\theta_e$ where phase detector gain $K = \frac{\hat{U}_i \cdot \hat{U}_r}{2}$,
Ui and *Ur* are amplitudes of the incoming signals, and θ is the phase difference.

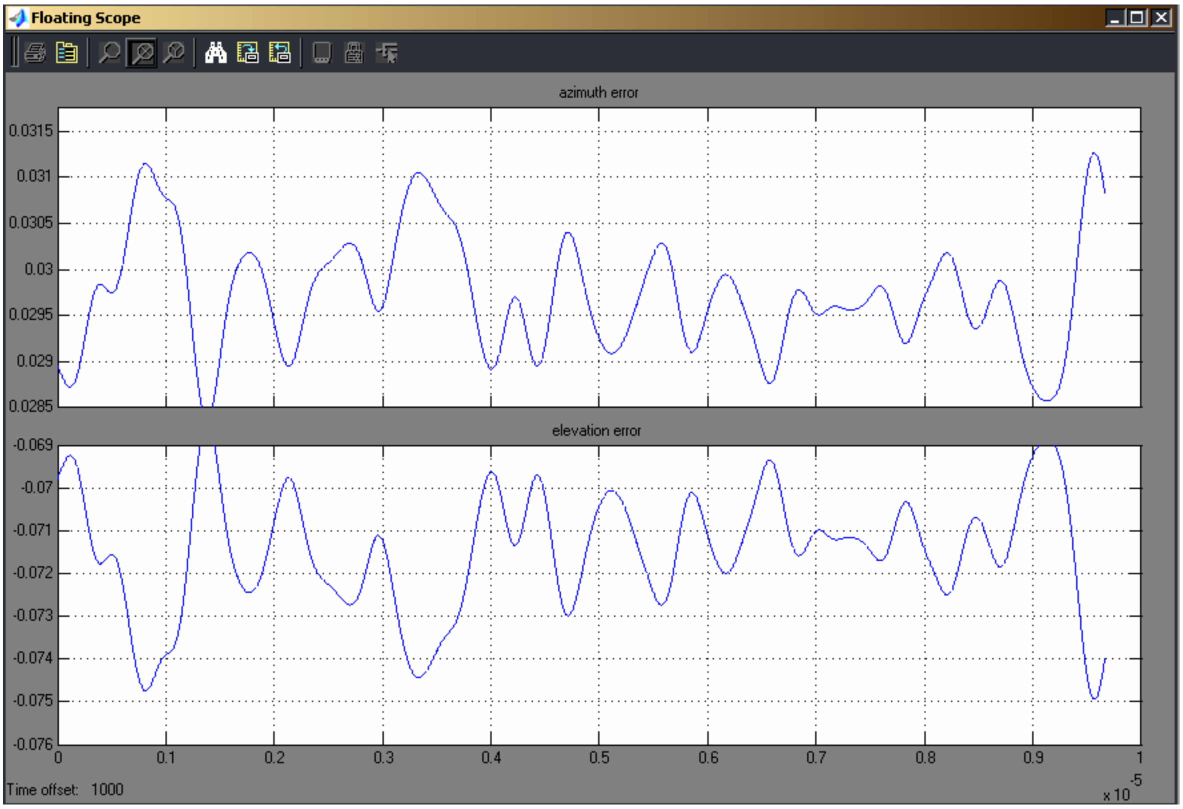


Figure 9.5.7: Azimuth and elevation error voltages after the phase detection stage.

9.5.7 Final results

Here are the final results of the simulation. As I have expected the system generated information in form of degrees in azimuth and elevation about how the pointing direction of the antenna system should be changed.

According to the simulation results the pointing direction of the antenna system should be changed by 1.72° in azimuth and 4.15° in elevation what brings the antenna system boresight to the former sector B, as expected.

To check that the system was really working I have traced the error signals from time offset like 0, to time offset like 100. Both signals fluctuate a bit but it won't be any problem for the antenna system that will react only on changes larger than 0.5°. As you can see from the test results given bellow, these fluctuations do not exceed values of 0.05°.

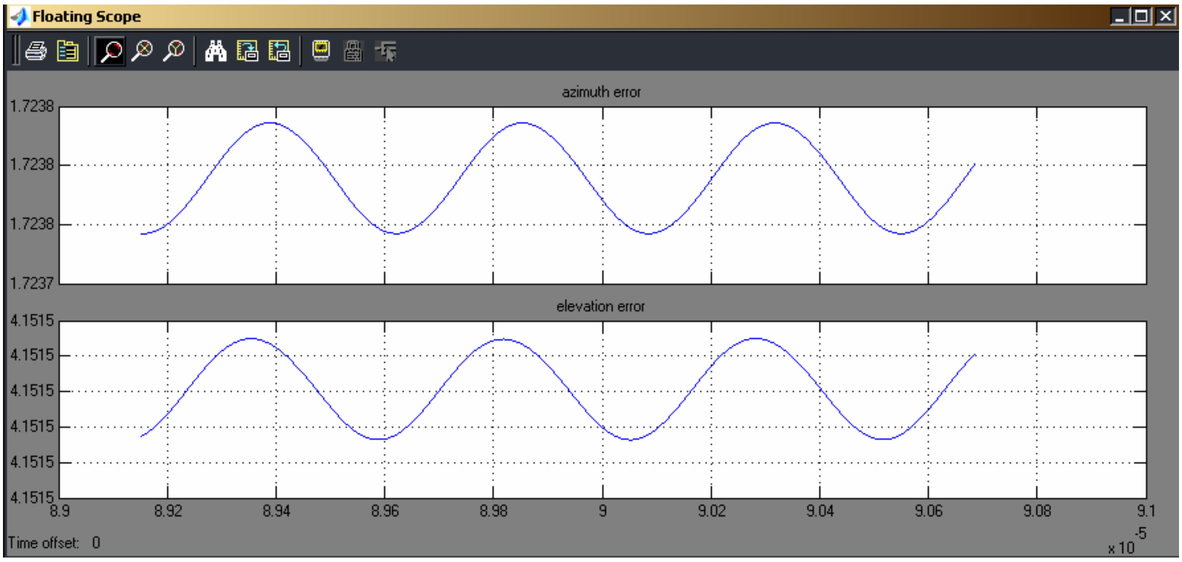


Figure 9.5.8: Output of the monopulse system in degrees of azimuth and elevation, time offset 0.

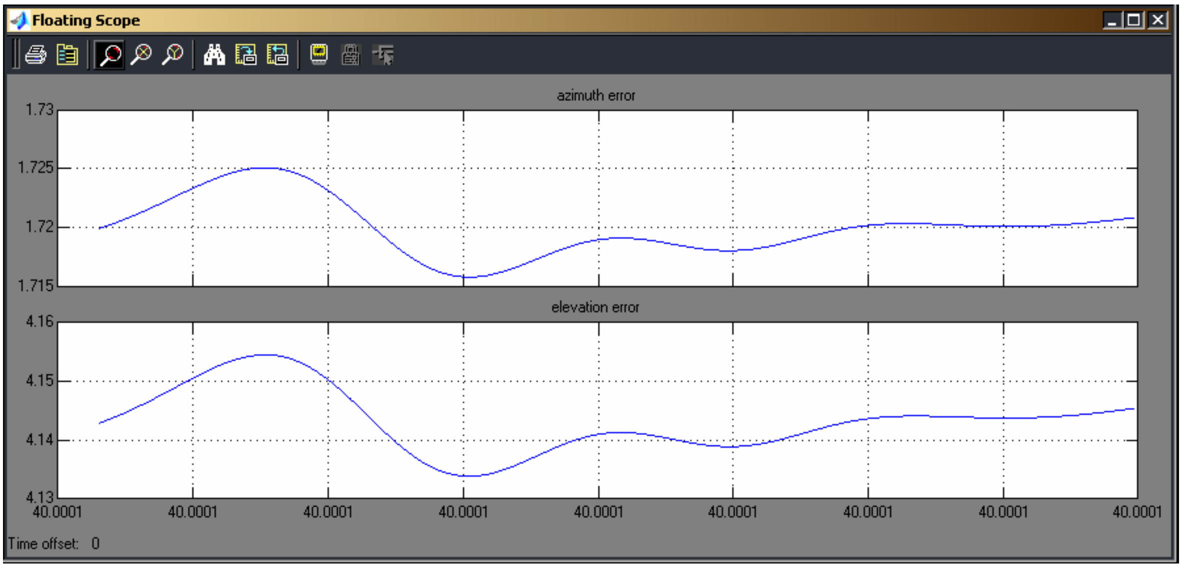


Figure 9.5.9: Output of the monopulse system in degrees of azimuth and elevation time offset 40.

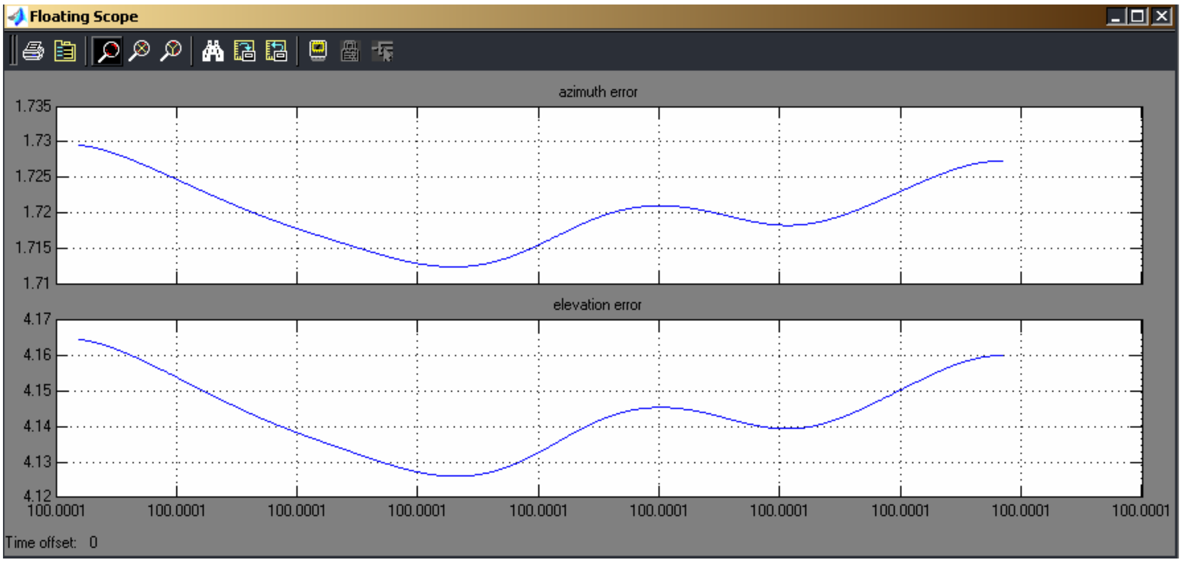


Figure 9.5.9: Output of the monopulse system in degrees of azimuth and elevation time offset 100.

10.0 Conclusion for the Monopulse tracking system design

As you can see from the previous chapters of this diploma report I have developed three alternative solutions for a monopulse tracking system design.
All three solutions are possible to implement, at least according to my theoretical studies of the problem. Each of the solutions is special concerning both technical configuration of the system and cost.

The first design should be the easiest one to build in reality and the most accurate one due to excellent characteristics of the monopulse IF processor from Radar Technology. At the same time this design is the most expensive one again due to the monopulse IF processor from Radar Technology.

Although I tried to simplify construction of the monopulse detector, it will be a real challenge to realize the second design on practice, since construction of the monopulse detector involves a lot of details to be taken care of.

The third design can seem to be a simple one but it demands knowledge of LabView or Visual Basic, so for them who have no knowledge of at least one of these programs this design will also be a challenge.

So, evaluating these three designs from the point of view of complexity and reality to implement on practice, I would recommend the third one.

I have also checked the prices for the necessary components to build each of the three designs. Here is a comparison of total costs of the designs:

	Design 1	**Design 2**	**Design 3**
Comparator network HW cost	1035.6 $	1035.6 $	1035.6 $
System HW cost	4870.0 $	232.8 $	842.8 $
Total cost	***5905.6 $***	***1268.4 $***	***1878.4 $***

Table 10.1: Comparison of total costs of the suggested designs, expenses for cables and connectors are not included.

Considering the cost of the system, the second design is the most appropriate one, but I have to mention again that I assumed that some of the components would be available at HIN, which means that some extra expenses should be expected.

At last, considering both design complexity and cost I think that the third one is the best solution. So in case there will be an opportunity to build a monopulse tracking system I would recommend the third design.

11.0 Suggestions for Future Development of the Monopulse Tracking System

In this diploma report I have suggested three possible solutions for the design of a monopulse tracking system and have simulated one of the solutions in Simulink.
The greatest challenge for the future will be to assemble a monopulse tracking system on practice.
In chapter ***10.0*** I have come to a conclusion that from the points of view of the cost and complexity of the system the third design, the one described in chapter ***8.3.0*** would be the best choice. So in case there will be an opportunity to build a monopulse tracking system I would recommend this design.

The main tasks in implementing this particular design on practice that I see for me now can be stated as follows:

- Assemble the antenna system
- Obtain all the necessary components
- Acquire a working knowledge of LabView or Visual Basic
- Simulate function of the monopulse detector in LabView or Visual Basic
- Assemble and test the whole system

I assume that probably, some of my recommendations given for this design will have to be reconsidered, but according to my studies of this design everything should work at least in theory.

12.0 Ground Station antenna system

The characteristics required for a ground station antenna can be specified as follows:

- High directivity along the axis of the antenna, in principle directed towards the nominal satellite position.
- Low directivity in other directions in particular those, which correspond to satellites other than that which it is required to establish a link to.
- Antenna efficiency as high as possible for both frequency bands (uplink and downlinks) on which the antenna operates.
- High isolation between orthogonal polarizations.
- The lowest possible antenna noise temperature.
- Continuous pointing in the direction of the satellite with the required accuracy.
- Limitation, as far as possible, of the effect of local meteorological conditions (such as wind, temperature, etc.) on the overall performance.

For a ground station antenna system the important parameters, which characterize the radiation of the major lobe, are the gain and the angular beamwidth.
The antenna system gain arises directly in the expressions for the effective isotropic radiated power (*EIRP*) and the figure of merit (*G/T*) of the station.

12.1 Polarization Pattern

12.1.1 Polarization Review

An antenna is a transducer that converts radio frequency electric current to electromagnetic waves that are then radiated into space. The electric field or "E" plane determines the polarization or orientation of the radio wave. Polarization of the ground station antenna system is circular. A circular polarized wave radiates energy in both the horizontal and vertical planes and all planes in between.

12.1.2 Horizontal/vertical, azimuth/elevation planes

A simple dipole antenna produces a signal polarized in the same plane as the antenna. A vertically mounted dipole (or array of collinear dipoles) produces a vertically polarized signal. Likewise, more complicated antennas, such as Yagi, with all elements in the same plane produce a signal polarized in the plane of the elements.

For example, a Yagi antenna can be used to produce a vertically or horizontally polarized signal depending on the mounting orientation of the antenna.

Antennas that produce a simple horizontally or vertically polarized signal can be represented by two antenna patterns: the pattern in the same plane as the elements, which is the pattern of the signal in the plane of polarization, and the pattern in the plane orthogonal to, or 90 degrees from, the plane of the elements (the "cross-polarized" signal). For antennas such as these, the azimuth pattern and the elevation pattern correspond to the co-polarized and cross-polarized patterns depending on the mounting orientation of the antenna. For example, if a Yagi antenna is mounted with the radiating elements oriented vertically it will produce a vertically polarized signal. The azimuth pattern would then correspond to the co-polarized pattern (in the plane of the elements, sometimes called the E-plane, or the plane of the electric field produced by the antenna). The elevation pattern in this example would correspond to the cross-polarized pattern (90 degrees from the antenna elements, the H-plane, or the plane of the magnetic field produced by the antenna). If the Yagi was mounted with the elements oriented horizontally, the azimuth and elevation patterns would be interchanged.

12.1.3 Polarization test

Performing this test I faced an important problem - lack of necessary equipment. Ground station handheld Kenwood radio has been disassembled during the balloon test at Andøya Rocket Range (June 2003). The reason why I had to wait with performing this test so long was that I waited for installation of the entire antenna system which has been accomplished right after the balloon test.

The only suitable piece of equipment I was left with was an UHF FM transmitter borrowed from Narvik amateur radio club. With its help I was only able to test polarization of the receiving antenna array of ground station antenna system.

As it has already been mentioned, a circular polarized wave radiates energy in both the horizontal and vertical planes and all planes in between. That is why I tested polarization of the ground station antenna receiving array in both vertical and horizontal planes as well as in 45°- plane in between the two planes mentioned above.

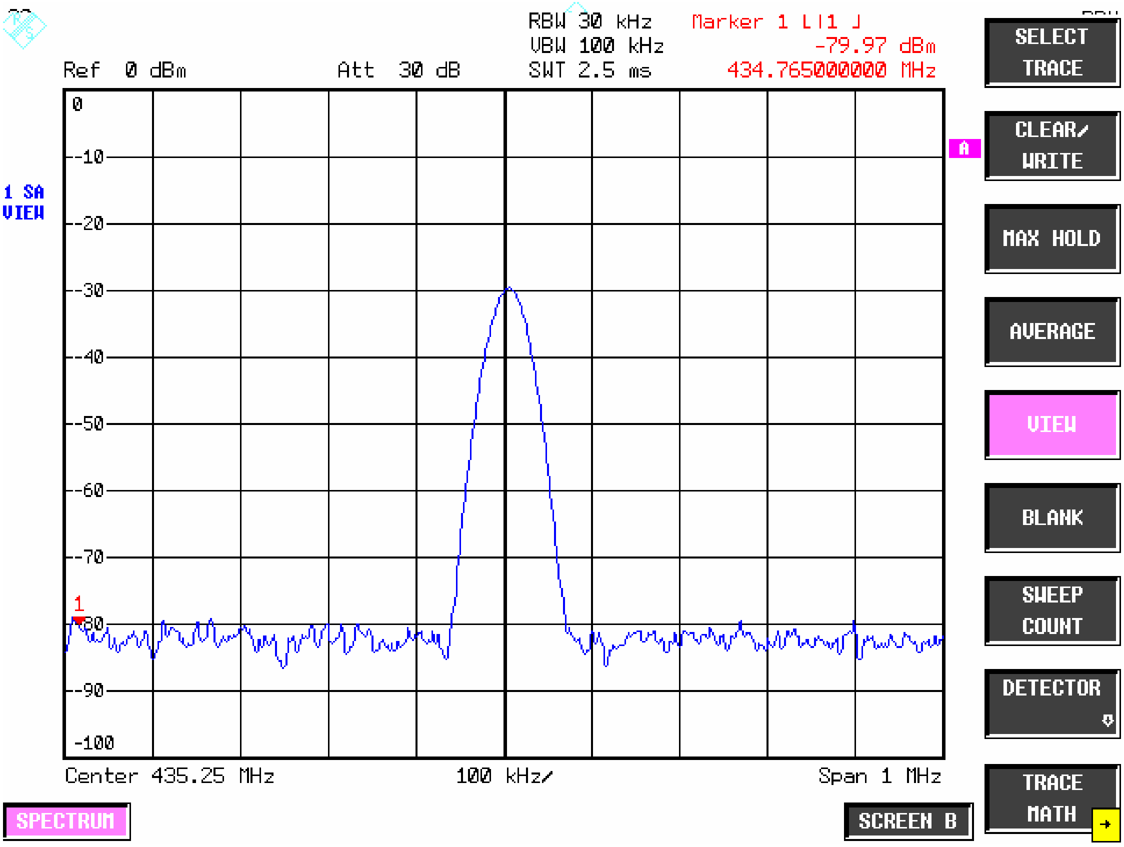


Figure 12.1.1: Polarization pattern test result of the ground station antenna receiving array in the horizontal plane.

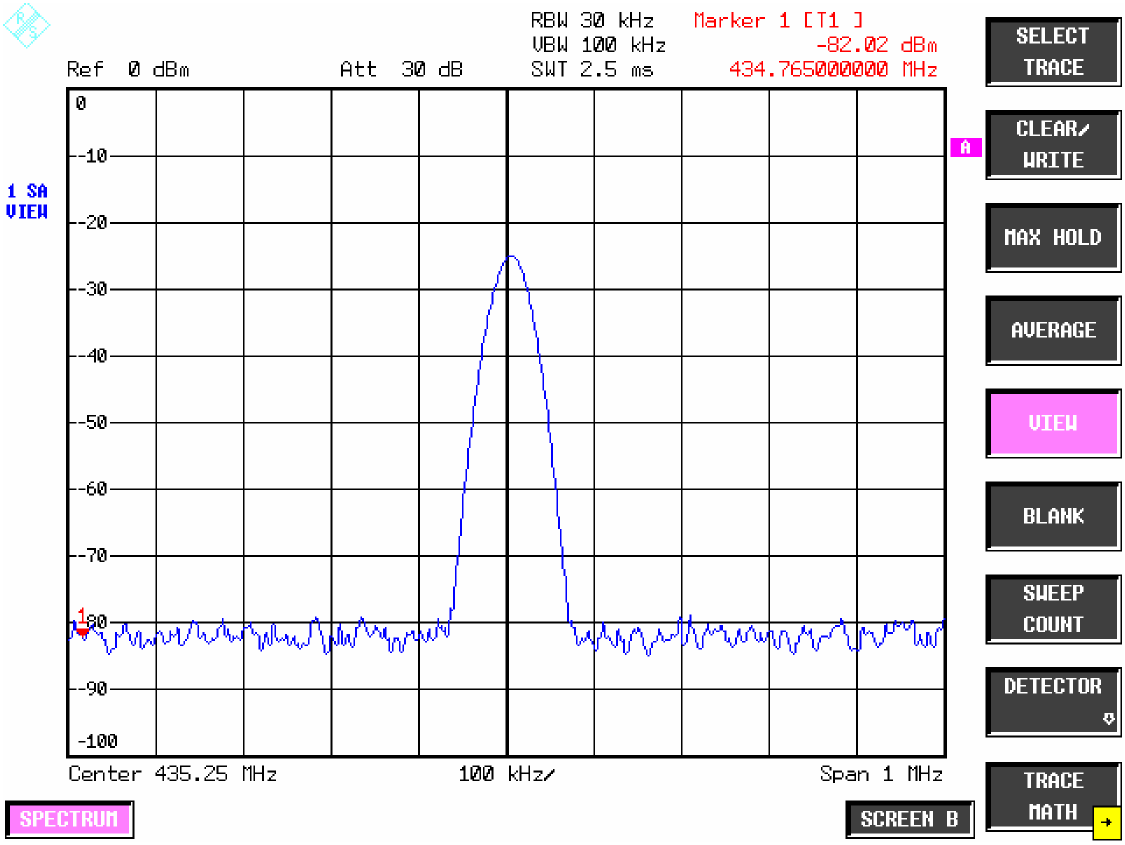


Figure 12.1.2: Polarization pattern test result of the ground station antenna receiving array in the vertical plane.

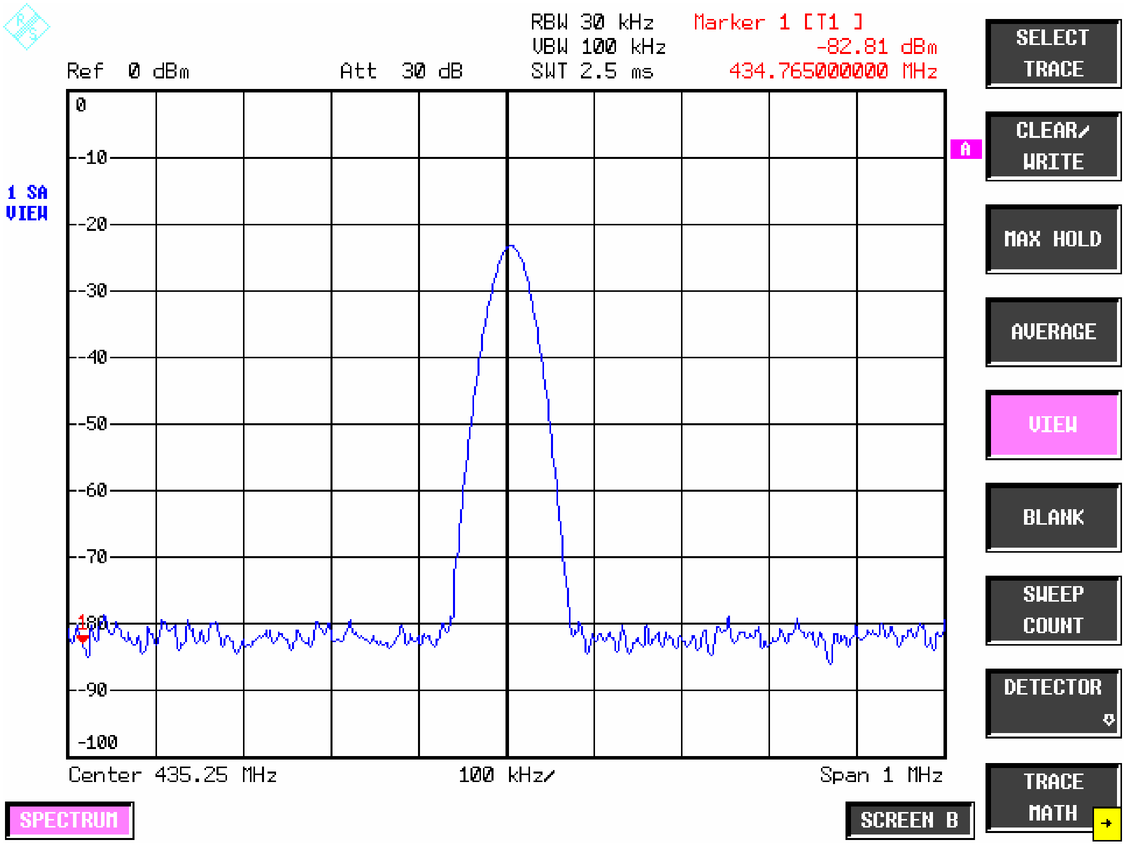


Figure 12.1.3: Polarization pattern test result of the ground station antenna receiving array in the 45°- plane.

Test results above confirm that the receiving array of the ground station antenna system has a circular polarization with axial ratio like 0 dB. Though difference in the radiation level on the graphs shown above can be confusing, it should be neglected because it only is a sender – receiver distance dependant factor.

Radiation pattern of the receiving antenna array has also been simulated in YAGIMAX, results of these simulations are shown bellow.

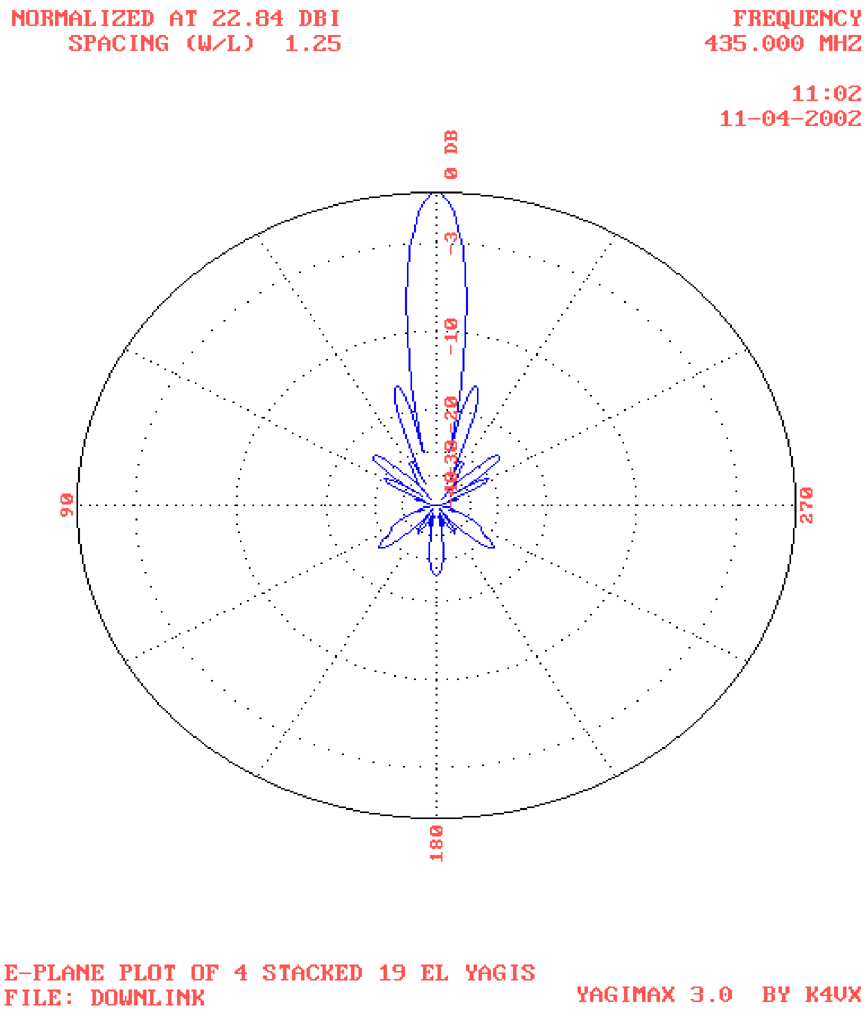


Figure 12.1.4: Simulation of the polarization pattern for the ground station antenna receiving array in E- plane.

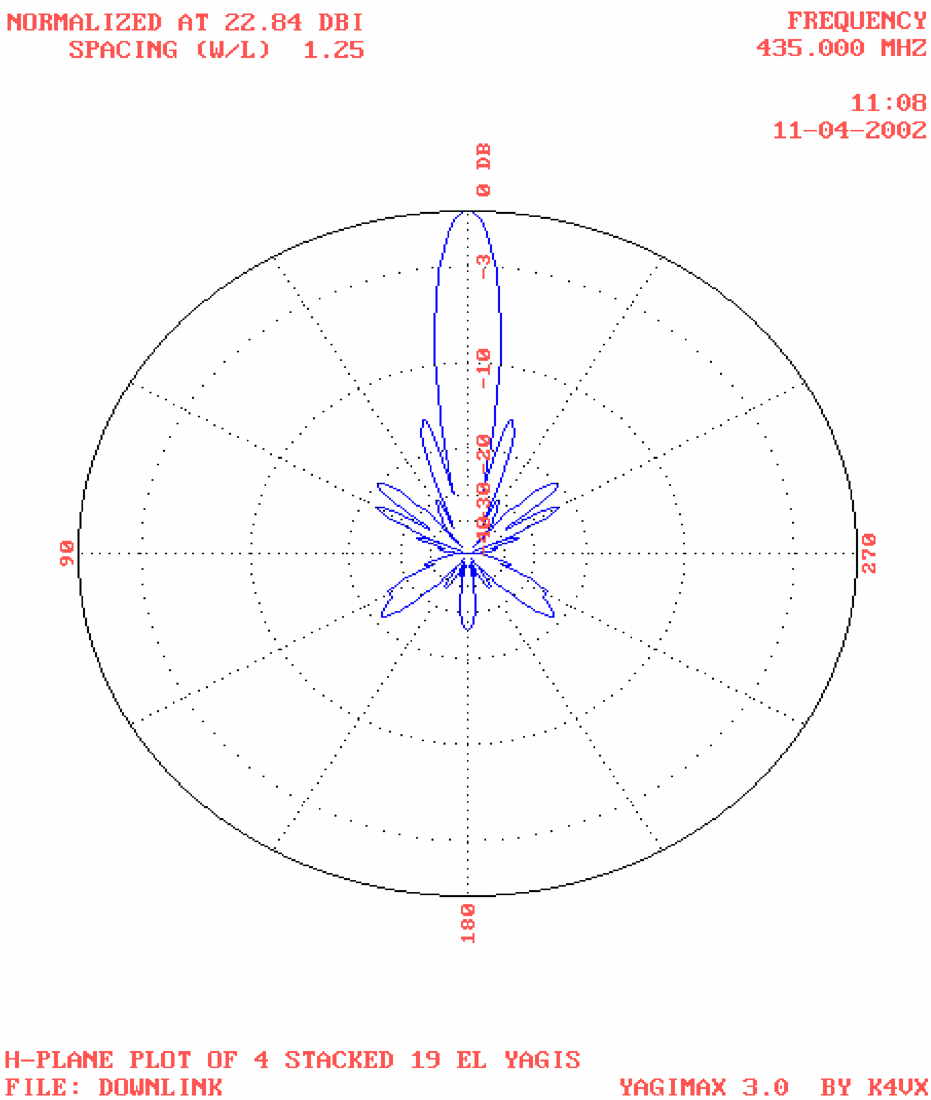


Figure 12.1.5: Simulation of the polarization pattern of the ground station antenna receiving array in H- plane.

12.2.0 Gain

Antenna gain measurement should give the angular variation of the test antenna's radiation. This test is needed to fully characterize the radiation properties of the test antenna.

Trying to perform this test I faced exactly the same problem as with the test of antenna system polarization pattern - lack of equipment necessary to perform this test, (the Ground Station handheld Kenwood radio was disassembled during the balloon test at ARR), which made it impossible for me to test the Ground Station antenna system gain. But as long as this test is a part of my diploma I would like to suggest a method that can be used for testing the antenna system gain.

The test technique that I'm suggesting to use is to measure the antenna's gain against a known reference. The equipment one needs is an UHF receiving antenna, a low-power transmitter, a receiver and a VU meter.

Any clear area can be an antenna range. The trick is to avoid obstructions and reflections: if the received signal is louder when the antenna is pointed away from the source, there is a problem.

To conduct comparison tests, two antennas should be placed side by side on masts of the same height, using equal length feed lines. A steady signal can be generated perhaps 40 wavelengths away, and detected on a receiver that is *not* overloaded but has its AGC disabled.
Then a VU meter can be used to indicate the difference in received signal strength of the two antennas. As a precaution, the two antennas can be swapped so that antenna #1 goes on the mast and uses the feed line formerly used by antenna #2. Given some care in measurements and a stable path, it is possible to determine the difference in the gain of the two antennas down to a fraction of a decibel.

A variety of element length and spacing combinations can be tried, if necessary, until the best results are achieved. While this is far more tedious than computer modelling, it does produce repeatable, practical real-world results.

12.3.0 G/T - A Receiving System Figure of Merit

The sensitivity of a ground antenna system is a function of many factors including antenna gain (*G*) and system noise temperature (*T*). A convenient figure of merit is the ratio (G/T) - the higher this ratio the better the sensitivity of the system to weak signals. To obtain *G/T* one could determine *G* and *T* separately, but these are difficult measurements. Fortunately it is relatively easy to obtain the ratio (*G/T*) by a single measurement (and a little arithmetic).

12.3.1 T - The Total System Noise Temperature

T is the total system noise temperature (in degrees Kelvin) and is equal to the sum of the noise generated in the receiving system (*Tr*) and the noise delivered from the antenna (*Ta*) when the antenna is looking at a region of the sky free of strong sources. *Ta* includes the galactic background temperature as well as additional noise picked up by the antenna sidelobes viewing the earth at ambient temperature.

The receiving system temperature (*Tr*) is related to the system noise factor (*Fn*) by:

$Tr = (Fn - 1)* 290$ **(eq 12.3.1)**

Where the noise factor (*Fn*) is simply the noise figure (*NF*) in dB expressed as a ratio:

$Fn= (Log \wedge -1)\ (NF / 10)$ **(eq 12.3.2)**

12.3.2 Determining G/T

The principle behind determination of *G/T* is to measure the increase in noise power which occurs when the antenna is pointed first at a region of cold sky and then moved to a strong source of known flux density - usually the sun.

This ratio of received power is known as the Y-factor.

$Y= Psun / Pcold\ sky$ **(eq 12.3.3)**

The following equation shows the relationship between *G/T*, the measured *Y-factor*, and the value of solar flux (*F*) at the observing frequency.

$G/T = (Y - 1) * 8 * pi * k * L / (F * \lambda^2)$ **(eq 12.3.4)**
where:

- Y = sun noise rise expressed as a ratio (not dB)
- k = Boltzmann's constant 1.38 *10^-23 joules/deg K
- L = beamsize correction factor
- λ = wavelength in meters (at the operating frequency *fo*)
- F = solar flux at fo in watts / meter^2 / Hz

12.3.3 Beamsize Correction (L)

The beamsize correction factor (L) is dependent upon antenna beamwidth and approaches unity for small antennas with beamwidth larger than a few degrees.

$L = 1 + 0.38 (Ws / Wa)^2$ **(eq 12.3.5)**
where:

- Ws = diameter of the radio sun in degrees at *fo*
- Wa = antenna 3 dB beamwidth at *fo*
-

The diameter of the radio sun (Ws) is frequency dependent. A value of 0.5 degrees for frequencies above 3000 MHz should be assumed, 0.6 degrees for 1420 MHz, and 0.7 degrees for 400 MHz.

Beamwidth of the antenna system of our ground station is larger than 2 degrees, that is why the beamsize correction factor L can be set like unity ($L=1$) and we can forget about equation 12.3.5.

12.3.4 Solar Flux Density (F)

The next term to be discussed, is (F) - the solar flux density at the test frequency. The USAF Space Command runs a worldwide solar radio-monitoring network with stations in Massachusetts, Hawaii, Australia, and Italy. These stations measure solar flux density at 245, 410, 610, 1415, 2695, 4995, 8800, and 15400 MHz. We are lucky enough to be operating near one of these eight "standard" frequencies, so all we have to do is use the reported flux density.

In case of operating between two given frequencies one will need to interpolate between flux densities at the lower and higher frequencies. The best interpolation scheme is to graph the flux density at several frequencies and use a curve fitting routine to determine the flux density at your operating frequency.

The solar flux density obtained from the USAF must be multiplied by *10^-22* in order to get the units correct for use in equation 12.3.4.

12.3.5 Measuring Y

The determination of *G/T* is completely dependent on an accurate measurement of *Y*. The easiest measurement technique is to use a power meter (or a true RMS voltmeter) connected to the receiver IF. For this measurement to work the receiver must be operating in a linear region.
The Y factor is simply the change in meter reading on and off the sun. The accuracy of this method is dependent on the linearity of both the power meter and the receiver.

To achieve a better result I made four measurements of *Y* and took an average. The solar flux measurements where obtained about at the same time I took measurements for calculation of G/T.

	P sun [mW]	**P cold sky [mW]**
1	0.46	0.015
2	0.51	0.018
3	0.46	0.018
4	0.44	0.015
Average	0.4675	0.0165
Y- factor	**25.32**	

Table 12.3.1: Measuring of the Y- factor.

12.3.6 G/T Calculation

The solar flux density at the test frequency of 410 MHz was reported to be
$30 \cdot 10^{-22} \dfrac{W}{m^2 \cdot Hz}$.

$$G/T = \frac{8 \cdot \pi \cdot k \cdot L}{F \cdot \lambda^2} \cdot (Y-1) = \frac{8 \cdot \pi \cdot 1.38 \cdot 10^{-23} \cdot 1}{30 \cdot 10^{-22} \cdot 0.7^2} \cdot (25.32 - 1) = 5.738 dB/K$$

To put it in perspective I'm going to do the calculation in reverse and estimate what values of G/T and Y are expected given an antenna size (gain) and preamplifier noise temperature.

Our antenna system has a calculated gain of 17- 19 dBi (power ratio of 1000) and the preamplifier is advertised to have a noise temperature of 120 degrees K. Further assumptions include 10 deg K due to the galactic background, 25 deg K due to spillover, 30 deg K due to 0.5 dB of attenuation between the feed and the preamp and 5 deg K due to the receiver and cable following the preamp. Therefore the total receiving system temperature is estimated to be:

T = 120 + 25 + 30 + 10 +5 = 190 deg K

The expected value of G/T is therefore *(1000/190) = 5.2 = 7.16 dB/K*

By the way, we can also do this calculation by converting temperature into dB referenced to 1 deg K. and leaving the antenna gain in dBi. Our temperature expressed in this way is

T dB = 10 Log (190/1) = 22.78

And *G/T* in dB is simply *(30dB - 22.78dB) = 7.21 dB*

So the expected value of *G/T* was 7.16- 7.21 dB but I measured 5.738 dB. Why? A number of factors could be responsible. First, I wasn't able to get any information about linearity of the power meter I used. Second, one can not be 100% sure that the theoretical calculation which is based on assumptions is the correct one. Third, it's time to make sure the feed is focused and free of bird nests, and that no unexpected losses exist in the receiving system.

As a conclusion to this test I would like to say that I think that the measured *G/T* value is more reliable than the calculated one, and I set the *G/T* value for the ground station antenna system like **5.738 dB/K**.

12.4.0 Conclusion on ground station antenna system tests

In this chapter I have written about the tests I have performed on the ground station antenna system, have shown the test results and made conclusions.

I wasn't able to test the ground station antenna gain because of lack of all the necessary equipment but I have recommended a method that can be used to perform this test.

There have also been performed tests on the ground station antenna diagram and tranceiving condition at ground level in Narvik, Kjellbåten, Ballangen and Ankenes. Results of these tests are described in detail in the diploma report of Åge-Raymond Riise.

13.0 Final Conclusion

In this diploma report I have looked at different solutions and made recommendations for hardware and design of a tracking antenna system for the nCube satellite project. All recommendations where made after thoroughly studies of different alternatives and theory behind the problem of this project.

Because of financial problems and lack of time, I have not been able to test any of the monopulse system equipment discussed in this report. Recommendations that I made in this report are based on theory and technologies tested in amateur radio projects.
Most of the hardware is standard equipment which is possible to buy at hardware and amateur radio stores, but some is made for military purposes, what makes it more complex and more expensive.

There is a probability that some of recommendations that I made will have to be reconsidered, but from the assumptions that I made working on this project everything should work, at least in theory and according to the simulation that I have made.

I have also performed some tests on the ground station antenna system polarization, overall system sensitivity and have recommended a possible method for antenna system gain measurement. According to these tests and the tests performed by other members of the Ground Segment group the ground station antenna system is working as it has been expected.

Appendix A: Theory behind a Hilbert transformer

A phase shift by 90º of all frequency components can be accomplished by using a Hilbert transformer.
A frequency response of the ideal continuous-time ideal Hilbert transformer can be derived. The Fourier transform of $\cos 2(\pi f_0 t)$ is

$$\frac{1}{2}\delta(f+f_0)-\frac{1}{2}j\delta(f-f_0) \qquad \textbf{(eq A1)}$$

The Fourier transform of $\sin 2(\pi f_0 t)$ is

$$\frac{1}{2}j\delta(f+f_0)-\frac{1}{2}j\delta(f-f_0) \qquad \textbf{(eq A2)}$$

Hence, the ideal Hilbert transformer has the following frequency response:

$$H(f) = -j\,\mathrm{sgn}(f) \qquad \textbf{(eq A3)}$$

where

$$\mathrm{sgn}(x) = \begin{cases} 1 & if \quad x > 0 \\ 0 & if \quad x = 0 \\ -1 & if \quad x < 0 \end{cases}$$

What is the magnitude response?
What is the phase response?
Why does the phase response change at the origin?
For $f_c > 0$,

$$\cos(2\pi f_c t + \frac{\pi}{2}) = \sin(2\pi f_c t) \qquad \textbf{(eq A4)}$$

For $f_c < 0$,

$$\cos(2\pi f_c t - \frac{\pi}{2}) = \cos(-(2\pi f_c t + \frac{\pi}{2})) = \cos(2\pi(-f_c)t + \frac{\pi}{2}) = \sin(2\pi(-f_c)t)$$

(eq A5)

What is the continuous-time impulse response of an ideal Hilbert transformer?

$$h(t) = \begin{cases} \frac{1}{\pi t} & if \quad t \neq 0 \\ 0 & if \quad t = 0 \end{cases}$$

for all *t*. It is a signal with two-sided infinite extent. It is not realizable.
An ideal discrete-time Hilbert transformer has the following frequency response:

$$H(\omega) = -j\,\mathrm{sgn}(\omega) \qquad \textbf{(eq A6)}$$

Its discrete-time impulse response is

$$h[n] = \begin{cases} \frac{2}{\pi} \cdot \frac{\sin^2(\pi n/2)}{n} & if \quad n \neq 0 \\ 0 & if \quad n = 0 \end{cases}$$

which is two-sided and infinite. The ideal Hilbert transformer is essentially a sampled version of $\frac{2}{\pi n}$ except that every even-indexed sample of $h[n]$ is zero. It is not realizable.
A discrete-time 90º-phase shifter can be implemented by an odd-length linear phase FIR filter. The discrete-time Hilbert impulse response would be shifted by L samples to the right and then truncated to $2L+1$ samples, where L is an odd integer since the even indexed coefficients are zero. This would yield a causal approximation to the ideal Hilbert transformer.

Appendix B: Another technique for measuring of Y- factor

Another and more accurate technique to measure Y- factor is to use a precision adjustable RF attenuator located between the preamp and the receiver. An RF power meter is connected to the receiver IF. Set the attenuator to 0 dB when the antenna is looking at the cold sky and adjust the receiver gain to get a convenient reference level on the power meter. Point the dish at the sun and crank in attenuation until the power meter once again reads the cold sky reference level. The Y factor is equal to the amount of attenuation needed to return the meter reading to the reference. This technique could also be used by measuring the DC output voltage from the receiver detector if a power meter is not available. Accuracy of the attenuator method depends on calibration of the attenuator - not receiver and power meter linearity.

Appendix C: Radiation pattern of the sender antenna of the ground station antenna system

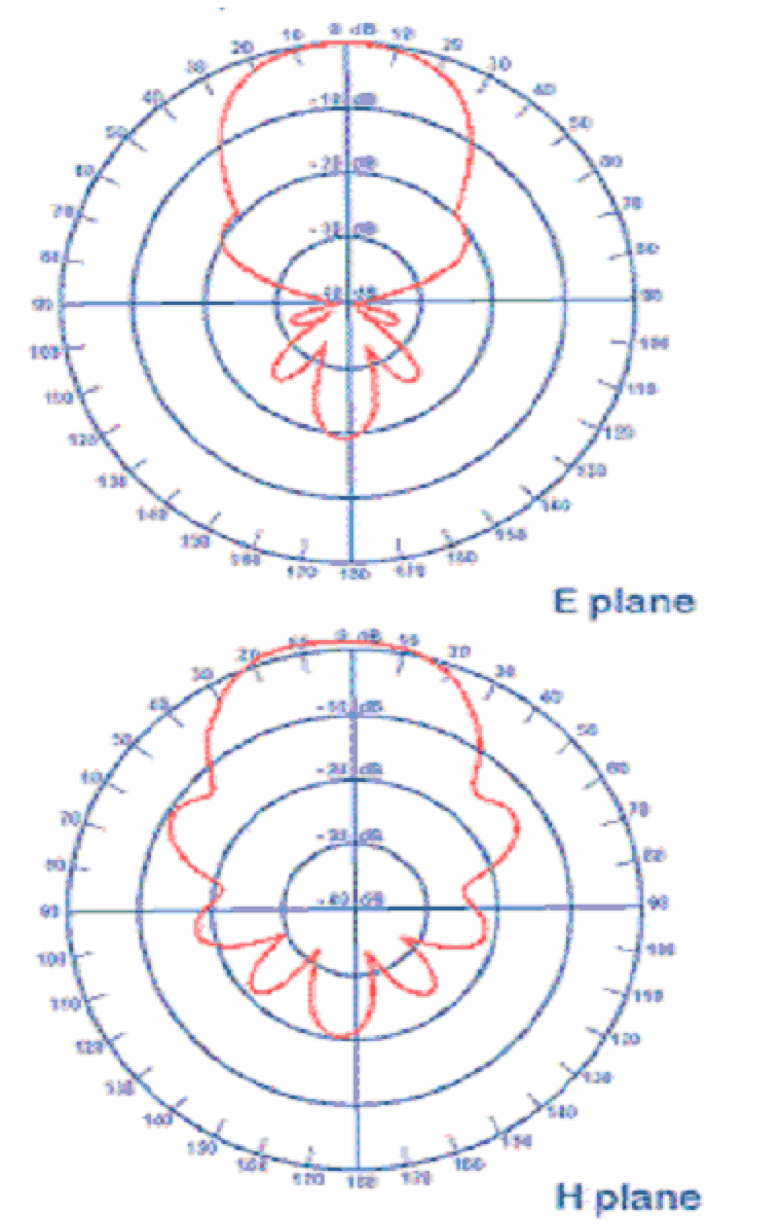


Figure C1: Radiation pattern of the sender antenna.

Appendix D: Layout of the AGC Amplifier circuit board

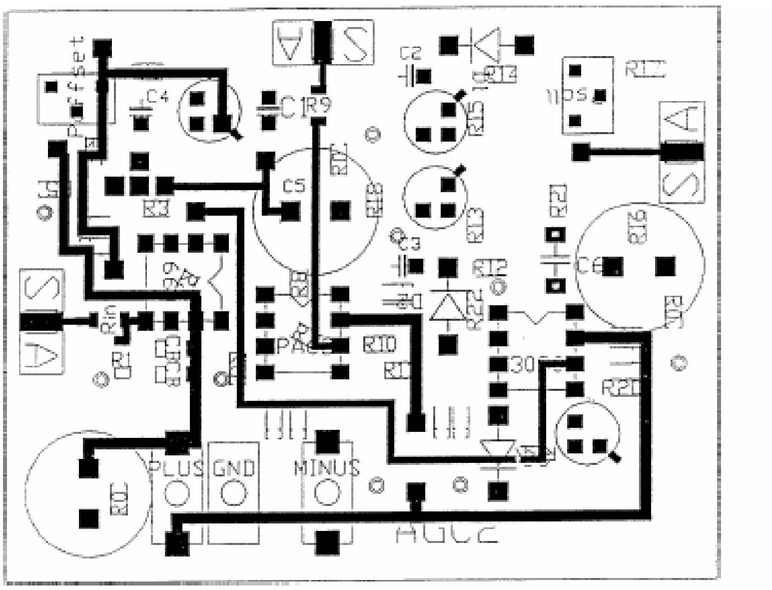


Figure D1: Layout of the AGC Amplifier circuit board – Back.

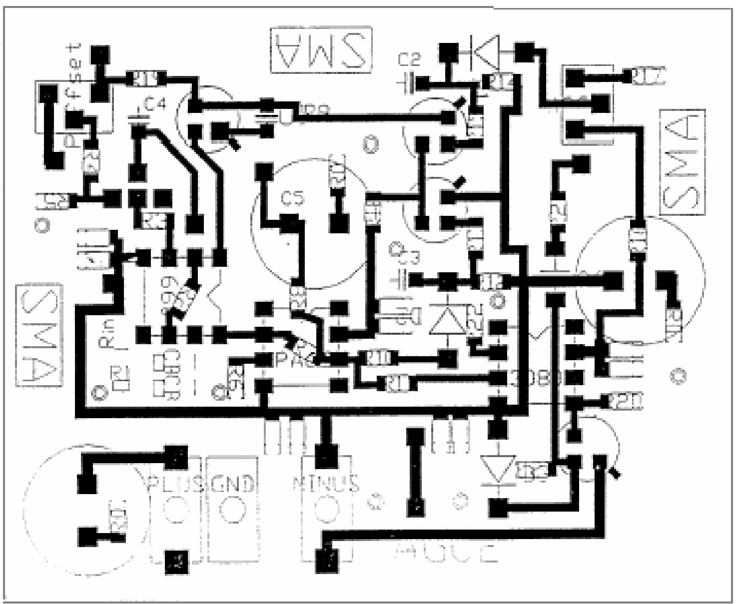


Figure D2: Layout of the AGC Amplifier circuit board – Back.

Glossary of terms

antenna array- a system of antennas coupled together to obtain directional effects or to increase sensitivity.

aperture- concerning a unidirectional antenna, that portion of a plane surface near the antenna, perpendicular to the direction of maximum radiation, through which the major portion of the electromagnetic radiation passes.

azimuth – the direction of the satellite from a terrestrial point measured clockwise from the north or south point of the meridian plane.

band-pass filter- a wave filter that has a single transmission band extending from a lower cutoff frequency greater than zero to a finite upper cutoff frequency.

closed loop- term applied to an electrical or mechanical system in which the output is compared with the input (command) signal, and any discrepancy between the two results in corrective action by the system elements.

coaxial cable/coax cable/coax- a cable or form of waveguide consisting of two concentric conductors- a central wire inside of and insulated from a grounded cylindrical braided wire shield. This braided wire shield minimizes radiofrequency and electrical interference.

conical scan- a tracking technique, where the receive frequency beam is rotated about the axis by a small angle. If the received signal has constant strength the satellite is on axis whereas if the signal rises and falls with rotation, there is a pointing error. The antenna can be programmed to track to a new pointing position according to the received signal state.

conjunction- the alignment of two objects in the solar system so that they have the same celestial longitude as seen from Earth.

directional antenna- an antenna that radiates or receives radio-frequency (RF) signals more efficiently in some directions than in others.

EIRP- means the equivalent isotropically radiated power, being the power supplied to the antenna, multiplied by the antenna gain in a given direction relative to an isotropic antenna.

hybrid (180°)- is a reciprocal four- port device which provides two equal amplitude in-phase signals when fed from its sum port Σ and two equal amplitude 180° out-of-phase signals when fed from its difference port Δ. Conversely, signals input into ports C and D will add at the sum port (B) and the difference of the two signals will appear at the difference port (A).

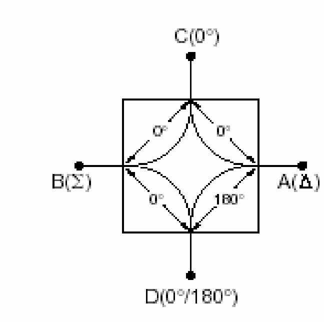


Figure GT.1: 3 dB 180° Hybrid.

voltage controlled oscillator (VCO)- an oscillator designed so the output frequency can be changed by applying a voltage to its control port or tuning port.

phase detector- provides a DC output voltage proportional to the difference in phase between two input signals.

mixer- A nonlinear circuit or device that accepts as its input two different frequencies and presents at its output
(a) a signal equal in frequency to the sum of the frequencies of the input signals,
(b) a signal equal in frequency to the difference between the frequencies of the input signals, and, if they are not filtered out,
(c) the original input frequencies.

monopulse- a tracking technique, where higher order asymmetric electromagnetic wave modes are generated in the antenna feed when the antenna is slightly off track from the satellite beacon. Extracting these modes at the beacon frequency allows a comparison to be made and error signals to be produced, which are used to activate drive motors, which minimize the tracking error. This arrangement uses a beacon frequency and allows automatic tracking without unduly affecting the performance of the communication channel.

polar orbit- an orbit around a planet that passes over or near its poles; an orbit with an inclination of about 90°.

programmed tracking- the satellite drift from its nominal geostationary position is small and since its movement is also slow it can be predicted. The antenna can thus be programmed to track the satellite.

sequential lobbing- the outputs of two antennas of the tracking system, which are pointed at slightly different angles, are sequentially sampled. The pointing error can then be derived by observing the relative amplitudes of these samples.

step tracking- a tracking system where the antenna is caused to turn a small pre-determined distance in one direction. If the received signal strength increases the system infers that the movement has been in the correct direction and makes a similar further move. A decrease in signal strength suggests an incorrect move and the antenna is turned to the opposite direction. The system will eventually home in on the correct pointing direction.

tracking- the process of following the movement of a satellite.

VU meter- a device for measuring the level of sound intensity.

X-Yagi/ crossed Yagi- is a right- hand circularly polarized Yagi antenna made with two sets of elements at right angles to each other.

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