EE3L11 - BEP

Semi Bistatic Radar

Subgroup - Receiver Antenna

Group H
Thesis

Delft University of Technology

Sander Renger, 4483510
Job van der Kleij, 4450906

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TU Delft Delft University of Technology

Challenge the future

Preface

This thesis is written in context of the Bachelor Graduation Project. The project was commissioned by the company Selfly with the goal to design bistatic radar with 2 portable platforms, an airplane/drone as a transmitter and a drone as a receiver. The goal was to design a system which could receive the transmitted signal from a distance of 50km between the receiver and the transmitter and 5 km between the receiver and the target.

We would like to express our gratitude to our supervisor dr. Faruk Uysal, for always having good advice and our supervisor dr. Ozan Dogan for his cunning remarks that helped us along greatly. Furthermore, we would like to thank our contacts at Selfly, Ronald and Jerom.

Finally we would like to thank our colleagues: Jeroen Blok, Marien Verseput, Mohammed Abo Alainein and Ossama El Boustani for an enjoyable and productive collaboration.

Sander Renger & Job van der Kleij
Delft, August 2020

Abstract

This thesis provides details about the design of a subsystem of a radar system designed for Selfly, who designed it to be used on places where the air traffic control is, due to circumstances, unavailable. The goal of the full system is to be able to detect objects during flight. To be able to do this a strong signal is required, this is made on a separate mobile platform, a plane or another drone.
The subsystem discussed in this report is tasked with receiving the signal, the requirements that come along with that task are quite formidable. After successfully finding the signal it is then used in an algorithm designed to estimate the angle at which the object is located.

Contents

Chapter 1

Introduction

With the current developments in drone technology, the amount of drones flying through the sky has increased dramatically. This will generate problems if it continues at the current rate. To counteract the problems induced by such a quantity of flying objects, this project has been used.
The focus lies on developing a system that can detect objects below or above the drone. Because of the range at which it will be used in possibly low visibility environments, a radar system is the most appropriate choice.
Due to the way it is being used, it should be small, light and cheap. This would make the design possible to be used for relatively small and commercially available drones, extending the range of possible customers.

1.1 Radar System

The purpose of our radar system is to detect objects at substantial distance. These systems have been large in both dimension and scope. This is primarily because of the range it wants to detect objects at. With large setups more power can be used. Since the system is large, it is often stationed in a static location. The system which is being designed requires to be portable and this brings formidable challenges.

The full system requires a signal to be transmitted from a base station and an arbitrary amount of receivers are required to receive the signal. The full system setup is shown in figure 1.1.
The idea of a radar system entails transmitting and receiving an electromagnetic signal. The full system is defined as a bi-static radar. This means that the transmitter and the receivers are on 2 different locations.

The full system consists of 3 main parts, designing a signal, transmitting said signal and receiving said signal. This thesis concerns the final one of these 3, receiving the transmitted signal. The most essential part of the receiver is successfully receiving the incoming signal.

1.2 Goal of the Receiver Chain

The main goal is to determine the angle of arrival (AoA) from incoming signals. This is done through a twin-receiver antenna (2 antennas) with a receiver chain which sends the improved signal to the Software-Defined Radio (SDR). The output at the SDR side gives an indication if an object travels from either above or below.
The setup for assignment 3 should just be the receiver, so it should be designed as a passive radar based

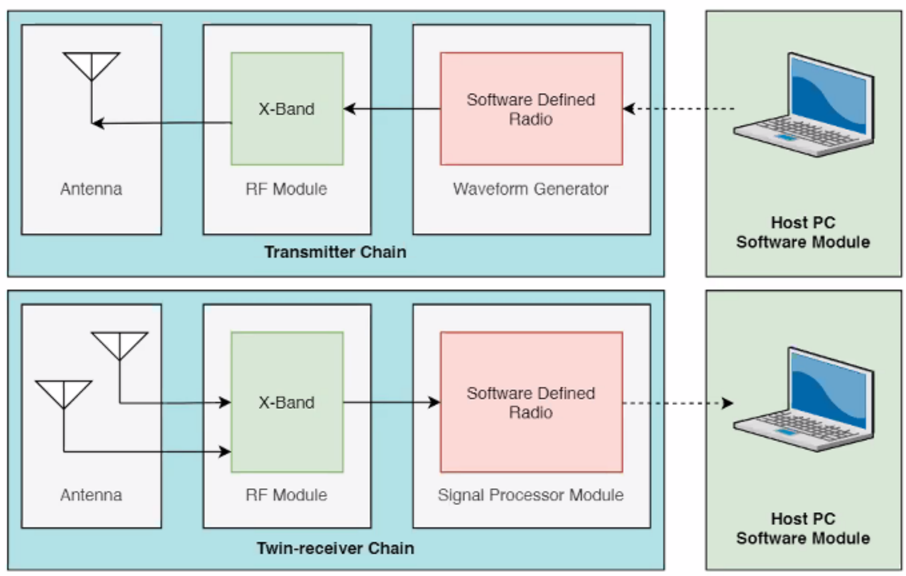


Figure 1.1: The full system setup

on a predefined signal. This signal will have to be chosen for this specific radar application in mind. The received signal is then processed by an algorithm inside the SDR to determine the angle of arrival.

1.3 State of the Art Analysis

In this section previously done research is taken and put into context for this thesis.
Standard research on bi-static radars is important, a bi-static radar is in essence a radar which has 2 separate locations, 1 for transmitting and 1 for receiving.
The work in [1] describes a method to solve problems related to direct and multipath interference. The work in [2] describes a multi-=channel passive radar based on frequency modulation (FM) signals. The work in [3] describes a radar which uses a transmitter of opportunity. In [4] an interesting setup is described which uses random illuminators (transmitters of opportunity) and uses those for implementing a FM airborne passive radar, a passive bi-static radar (PBR) (continuation on [2]).
For the design of the receiver few different parts are required, first and foremost, antennae and the SDR. These 2 components are very important because they determine the input and output requirements respectively. There are some overarching characteristics which should be equal to both. Standards on the SDR are therefore quite useful [5].
Because we are just making a receiver chain and the input was unclear for some time, we did some research on passive bi-static radars. These use random signals as illuminators, therefore they constitute an interesting choice. An implementation could be made without knowing the exact signal which will be used. In [6] a system is used to test drone detection with PBR with a central transmitter (SO) from a preexisting design. PBR with satellite signals, combined tracking and imaging [7]. Focus on reducing costs of PBR systems, with possible extension to Digital Video Broadcasting Terrestrial (DVB-T) signals [8].
For the algorithm some preparations were done as well, primarily focusing on already existing algorithms and their strengths. In [9] an analysis of mono-pulse was done and the performance was compared against both SAR and DBS in forward-looking imaging. In [10] it shows how mono-pulse angle tracking system tackles Phase shift, by comparing both the difference and summation signals. The already frequently used

angle measurement method in mono-pulse phase comparison is used on a virtual array MIMO radar, resulting in a higher accuracy than an actual MIMO radar array [11]. Multiple antennae configurations are tested for simulating AoA finding performance [12].

1.4 Subdivision of the Receiver Chain

The purpose of the receiver chain is to decipher the signal and use the characteristics to determine the angle of arrival. This is possible with different algorithms, which often use different components of the signal to determine the AoA. Due to it being a radar application some problems can be identified surrounding the inconsistency of the signal characteristics across the multiple inputs.
The construction of the full chain and algorithm is divided into multiple parts, the design of the chain, the design of the algorithm and the implementation of the chain itself. The design phase for the chain focuses around the possibilities and requirements of the chain. The design phase of the algorithm discusses the different algorithms, our choice and the workings of the algorithm which was implemented. The target of the chain is to produce a real life implementation, primarily focusing on price and feasibility.

1.5 Document Structure

The structure in this document will be divided in 3 main parts: design of the receiver chain, implementation choices and design of the algorithm. The design of the receiver is discussed in Chapter 5, with the design phase and elaboration on all components. The implementation choices are elaborated more on in chapter 6, where these discussions are ordered per component. The design of the algorithm is further discussed in chapter 7.
Simulations of the AoA algorithm are discussed in chapter 8.
The results are further discussed in chapter 9.1 and the possible continuation on this project is discussed in chapter 9.1.

1.6 System Design Choices

The general system design choices are shared between all subgroups. The main choices concern transmitted power, frequency band and bandwidth of the signal. For a radar, the transmitted power and the frequency determine the maximum range. The frequency has the secondary characteristic that it determines the wavelength and thereby the smallest object that the signal can reflect off, so the radar can detect. These characteristics are therefore a very important factor of the system and need to be carefully considered.

1.6.1 Transmitted Power

The main function of the amount of transmitted power can be seen if you look at the radar range equation 3.2, the 2 variables that are not static in our case are P_t and R^4. These 2 vary according to one another, the conclusion to reach from this equation is that the transmitted power has a big influence on the maximum range the setup is able to achieve.

1.6.2 Frequency Band

The frequency band of the signal is in the X-band. Frequencies range between 8 and 10 GHz. The higher frequency results in a lower wavelength which is required for detecting smaller objects. The lower wavelength does however result in a lower maximum range as a downside. Another main benefit of the x-band is the antenna required for both the receiver antenna and the transmitter antenna.

1.6.3 Bandwidth of the Signal

The bandwidth of the signal has a direct correlation with the power contained within said signal. To accurately be able to determine if the signal has been found, the signal needs to contain a high amount of energy. This is determined by the pulse width and the bandwidth has a direct correlation with the pulse width. Pulse width therefore constrains the maximum detection range of a target. The biggest trade-off of a high bandwidth is the hardware required to support said bandwidth, which easily becomes quite expensive.

Chapter 2

Program of Requirements

2.1 General Requirements

The Bi-Static Sense and Avoid System for Drones (BiSAD) includes a transmitter & receiver chain, and signal design. BiSAD is not merely composed of the three mentioned parts, the entire system includes a compunction link between drones and the mother-ship and software that implements localisation of the drones and the targets detected by the bi-static radar. The scope of the project is limited to the design of the transmitter and receiver chain and the radar waveform. The general requirements address these three parts of the Bi-Static Sense and Avoid System for Drones.

2.2 Assumptions

The scope of the project is limited to the design of the transmitter and receiver chain and the radar waveform. To simplify the project and ensure feasibility, especially during the COVID-19 pandemic, it is assumed that the project owner Selfly EDA already has the software packages necessary to implement positioning of the mother-ship and drones using GPS and localising the targets on a Plan position Indicator (PPI) and visualising the targets on a map.

2.3 Mandatory Requirements

The mandatory requirements specify the requirements that ought to be complied with at all times. These are subdivided into two categories, functional requirements and non-functional requirements. The functional requirements describe what the system/product does, and non-functional requirements describe attributes the system/product has got to have.

2.3.1 Non-functional Requirements

- The receiver must have reception of the direct-path from the transmitter up to 50 km.
- The receiver must have reception of echoes reflected from target within a radius of up to 5 km.
- The position of the reflection must be determined within 300 m accuracy.
- The system should be compatible with the requirements of Agentschap Telecom.

- The transmitter and receiver should be built with commercial of the shelf (COTS) equipment.
- The transmitter should use at most 3 kW of power.
- The transmitter should weigh at most 10 kg.
- The receiver is based on current Software Defined Radio capability.

2.3.2 Functional Requirements

- The system should detect objects with the size of a C-172 aircraft and bigger within the range ($\sigma \geq 1$ m^2)
- The system should determine the Direction of Arrival (DoA).
- The system should determine the distance between receiver and targets.

2.3.3 Trade-off Requirements

- Radio Frequency (RF) in X-band.
- Intermediate Frequency (IF) in range supported by the selected SDR.

Chapter 3

Basic Theory

This chapter explains some basic equations and concepts which will be utilised later on in the thesis.

3.1 Basic definitions

What	Symbol	Value	Unit
Constants			
The speed of light	c	$3 \cdot 10^8$	m/s
Boltzmann constant	k	$1.38062 \cdot 10^{-23}$	$m^2kgs^{-2}K^{-1}$
Standard room temperature	T_0	290	K
Variables			
Time	t	-	s
Wavelength	λ	-	m
Radar Cross Section (RCS)	σ	-	m^2
Centre frequency of the signal	f_c	-	Hz

The wavelength (λ) is defined as in equation 3.1.

$$\lambda = \frac{c}{f_c} \tag{3.1}$$

3.2 Radar Range Equation

The radar range equation is used to determine characteristics of the workings of a radar based upon a few specifications. This equation has a basic form which is shown in equation 3.2 [13].
Differences to the equation are done on a case by case basis, for our purpose we wanted to keep it as simple as possible, therefore we have not edited the equation to start off with.

$$P_r = \frac{P_t \lambda^2 G_t G_r \sigma}{(4\pi)^3 (R_t R_r)^2} \tag{3.2}$$

With:
P_t: the transmitter power [W]
P_r: the received power [W]
G_t: receiver antenna gain
G_r: receiver antenna gain

R_t: the distance between transmitter and target [m]
R_r: the distance between receiver and target [m]

3.2.1 Dynamic Range

The dynamic range is defined as the difference between the maximum and minimum power at the output of the receiver antenna. This is often calculated with free-space path loss and the radar range equation [14].

$$D = \frac{P_{r_{max}}}{P_{r_{min}}} \tag{3.3}$$

With:
D: the dynamic range
$P_{r_{max}}$: maximum receiver power [W]
$P_{r_{min}}$: minimum received power [W]

3.3 Free-Space Path Loss

The Free-Space Path Loss (FSPL) is the amount of loss which comes from the signal dispersing in free-space. Take for example a cone, the amount of surface at the start of the cone is less than the amount at the end of the cone. In free-space, the amount of power is distributed across the full size of the surface, so the further away the signal gets, the less power is received per surface area [15].

$$\text{FSPL} = (\frac{4\pi d f_c}{c})^2 \tag{3.4}$$

With:
FSPL: Free-Space Path Loss
d: distance between the antennas [m]

3.3.1 Noise Power

This comes from the noise temperature in combination with the noise bandwidth. This is the white noise which originates from the free space in combination with the extra noise added by the components.
The overall equation is obtained from utilising the fact that the power is divided across the available bandwidth, and the equivalent temperature is the noise induced by components [13]. The noise bandwidth is defined by the pass-band of the band-pass.

$$P_n = kBF_{eq}T_0 \tag{3.5}$$

With:
P_n: the noise power [W]
B: the bandwidth [Hz]
F_{eq}: the equivalent noise factor of the total system [K]

3.3.2 Doppler Shift

The Doppler Shift (or the Doppler effect) is the effect which shows changes in frequency due to differences in velocity between the object in question and the observer. In our setup this happens to the transmitter, the target and the receiver, thereby creating some possible frequency fluctuations.

The Doppler shift can be defined according to the change in frequency, this is shown in equation 3.6.

$$\omega_D = 2\pi f_D = 4\pi \cdot V \cos\theta / \lambda \tag{3.6}$$

With:
V: velocity difference between object and observer [m/s]
θ: the radial velocity [rad/s]

For regular frequency this gives $f_D = 2V \cos\theta / \lambda$.

Chapter 4

System Overview

The receiver chain part of the system should contain a chain which gets a signal as input, inputs that into the SDR and then uses an algorithm to output an angle that can be utilised by the main station for calculations. To use the chain effectively for that purpose with the specifications from the other subgroups, some requirements are easy to determine.
These include:

- SDR with a bandwidth of more than 15 MHz
- SDR which has multiple input ports
- receiver chain which provides enough gain for the SDR
- components which limit the introduction of noise in the chain
- possibly protection for the sensitive components in the chain

These specifications show that the vital choice in this design is the SDR, the SDR is the main component which constraints the chain.

4.1 SDR

As stated before, the SDR is the most important component, but it is also the most problematic component. It is the combination of a few components with the purpose of creating a radio, but one which can additionally perform some digital signal processing parts.
Because of the fact that it is a fully functioning radio, the specifications are static. Therefore the SDR must be chosen quite carefully. Because it is bought as a complete package, the quality and specifications can vary drastically. The amount of commercially available SDRs is quite low as well.
The main benefit of using a commercial available SDR was that a design for a super-heterodyne receiver and hard to implement signal processing was not required.

The 3 requirements which were the most important for the SDR were the bandwidth of the transceiver, the tuning range and 2 or more channels of receiver input. The X-Band requirement meant that the tuning range needed to be between 8 and 10GHz, this was not possible to be attained within our projected price for the full chain, therefore we opted to go for a mixer circuit with which the centre frequency was lowered to within the tuning range of the SDR.

The bandwidth was a requirement that could not be relaxed, therefore the chosen SDR had to have a bandwidth which was at least the required bandwidth of the signal.
The final requirement was that 2 or more antenna inputs were required to be used for the algorithm, and therefore also required as inputs on the SDR. This was a requirement for which we might take an additional SDR to fulfill it, but due to price constraints and implementation issues this was not possible nor desirable. The SDR which is chosen is the bladeRF 2.0 micro xA4 (A.4.10).

Figure 4.1: The chosen SDR - bladeRF 2.0 micro xA4

Afterwards, on basis of this decision, we had to find out the specific ADC requirements that would limit the receiver chain in a gain perspective. With the values found in the datasheet of the ADC in the SDR (the AD9361 A.4.11) we determined the required gain to be able to quantise the lowest signal that was needed to be able to be received. Apart from providing enough gain for the smallest possible signal, the maximum received signal should not exceed the maximum accepted power with the gain provided.

Chapter 5

Receiver chain analysis

The objective of this thesis is to make a chain of components which is able to receive and decipher the signal sent by the transmitter in such a way that it retains the highest possible information content.
To achieve this, the signal, which is transmitted by the transmitter chain, is received by the antenna and put through a carefully selected list of components. The signal itself loses power due to free-space path loss (FSPL) in the air. The reflection loss comes from the reflection off of objects. The reflection is not always present in the signal, the direct path signal does not reflect off of an object, but instead moves directly to the receiver in a straight line.
Once it enters the antenna new losses and gains are introduced by the components in the chain. Apart from those gains and losses, properties of the signal itself are edited. This is desired, the problem is that those components add noise. The main goal of designing the chain is to make sure that the output of the chain has the desired characteristics, whilst minimising the negative impact on the signal quality. The primary goal is to increase the amplitude of the signal to a desired value whilst keeping the noise manageable and therefore keeping the Signal to Noise Ratio (SNR) high.

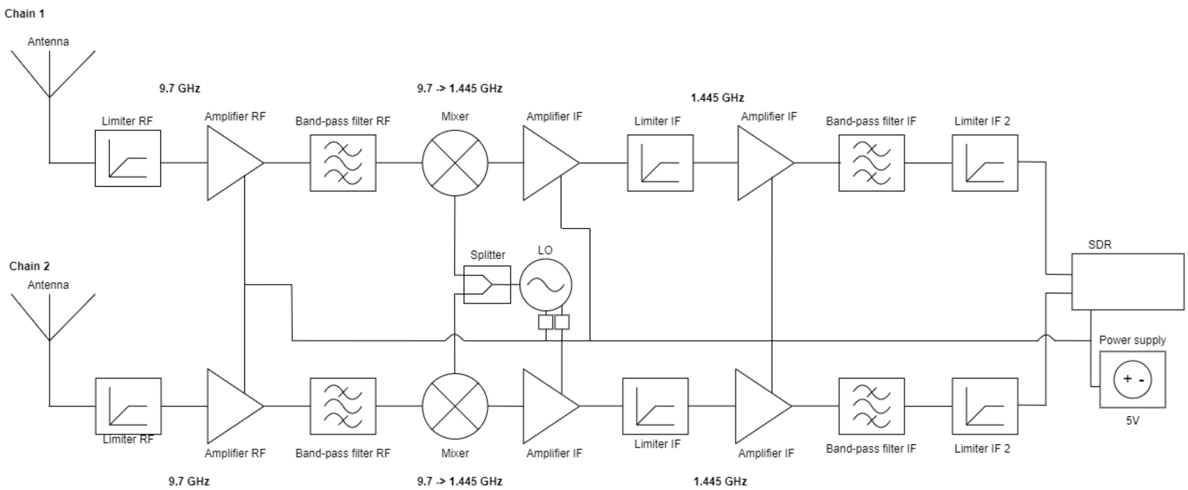


Figure 5.1: Proposed chain for the receiver part of the system

5.1 Full Design

For receiving a signal on the chain, the chain needs to be designed with an antenna that has a frequency range that contains the centre frequency of the signal produced at the transmitter antenna. The goal of the chain is to be able to digitize the signal at the output of the chain. The output of the chain is the input of the SDR.
For this purpose, some of the properties of the signal need to be adjusted. A Low Noise Amplifier (LNA), multiple filters and a mixer are utilised to achieve this. A big part of the design phase was selecting a suitable SDR to account for the overall requirements of the system.
When the SDR was selected the real design process of selecting the other components started. The problems that arose came from the values for which we designed the receiver chain, due to some calculation errors this process had to be repeated several times.
The final chain we designed for the purpose of receiving the signal is shown in figure 5.1. A figure with more information is available in appendix A.2.
The receiver design is split up in two parts based on their respective frequencies.
The first part, Radio frequency (RF), is the part with the incoming Radio signal and runs at 9.7GHz. The second part, Intermediate Frequency (IF), is the part after the mixer where the frequency is lowered to 1.445GHz.

5.2 Components

The full design of the receiver chain has been discussed in the previous section. In this section we will explain the different components that are utilised in the chain and the reasoning behind using these components.

5.2.1 Radio Frequency Part

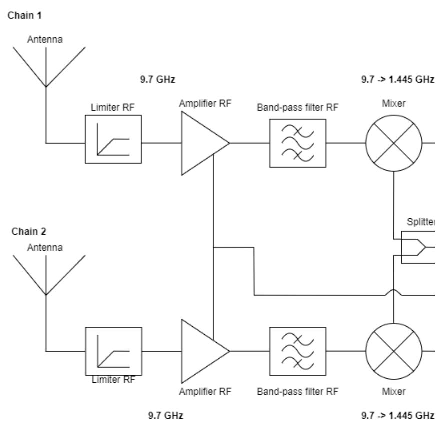


Figure 5.2: Proposed chain for the RF part of the system

In the radio frequency part, the chain is defined as the part which works under 9.7 GHz.
The Radio frequency part consists of 4 components:

- Antenna
- RF limiter

- RF Low Noise Amplifier
- RF band-pass filter
- Mixer

These components will be shortly discussed why they are used and their main properties.

Antenna

The main properties to consider about the antenna for our purpose are the frequency and the size. For the frequency, it has to have a centre frequency around the chosen frequency, this is 9.7 GHz. The size is determined by the algorithm that is being used. The antennas should be placed around $\frac{\lambda}{2}$ m apart.
The antennas which were discussed had problems in either radiation pattern or size, an omni-directional antenna was preferred, but the size and gain were a problem. Due to size constraints, the choice has been made to use a patch antenna.
Designing the actual patch antenna is outside the scope of this thesis and therefore a recommendation of characteristics is discussed.

Specifications

General design of patch antennas shows that the length constitutes of slightly less than 0.5 times the wavelength as a maximum. This would fall nicely with the requirement for the setup of the array with 0.5 times the wavelength as a maximum between every antenna.
The filter of the antenna (which simulates the effect of how the antenna reacts to signals with different frequencies) has a good characteristic for receiving narrow-band frequencies.
The radiation pattern from figure 5.3 is utilised to make an educated estimation for the gain of our antenna.

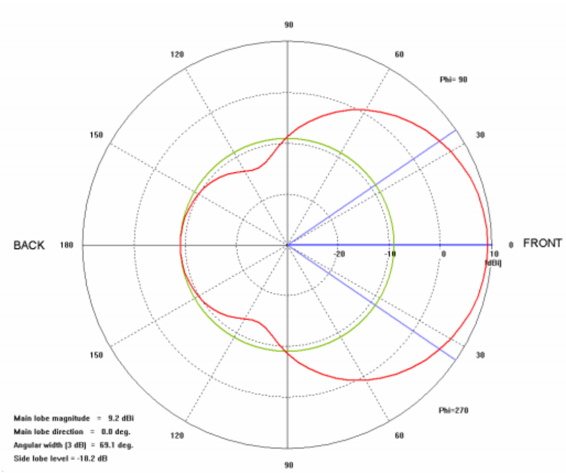


Figure 5.3: Radiation pattern from patch antennas

The antenna will have an area of importance of about 90 degrees, the gain for the patch antenna then equates to 3 to 8 dBi. These values have been chosen below the values derived from the figures due to expectations that the design will be less efficient.
The final specifications will be a centre frequency of 9.7 GHz, bandwidth of at least 50 MHz and a gain of 3-8 dBi.

Antenna Placement

The placement of the antennas on the drone is of vital importance for the workings of the system. On many of the locations which we considered there were significant drawbacks on range, distortion and maximum possible azimuth angle. This is primarily due to the drone itself, it blocks the signal with its body. Therefore the best option we found was to make a separate construction which can be mounted in a spot with less interference from other parts, such as higher or lower than the rotor.
This option can be seen in 5.4.

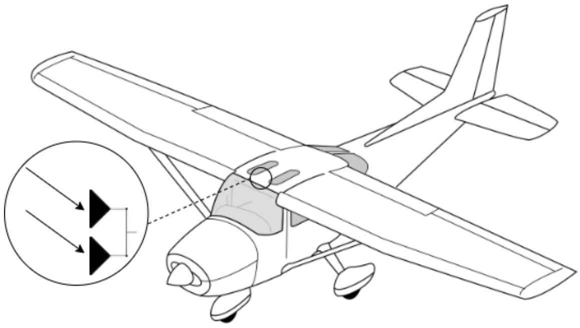


Figure 5.4: Placement of antennas

Antenna Design

For the design of the patch antenna we have looked at two research papers [16] [17], these discuss in detail the design of a patch antenna suitable for X-band operations.
For the design we recommend focusing on [17], the antenna discussed closely resembles an antenna suitable for our project. The final dimensions and target frequencies should be lowered.

RF Limiter

A limiter reduces the output power once the input power exceeds the level specified as the threshold by the limiter. The limiter then reduces the output to the given threshold for as long as the maximum power is not exceeded by the input power on the device.
Its purpose would be to protect sensitive components which might get damaged by excessive power.
The limiter situated here aims to protect the RF LNA and the mixer from high amplitude signals. The mixer is protected from damage by the limiter, but it does not guarantee proper operation at the level of power at which the limiter is required.

RF Low Noise Amplifier

A Low Noise Amplifier (LNA) is an amplifier with a low noise figure, which is usually situated at the beginning of the chain. This is because its low noise figure and high gain makes the noise figure of the components which follow the LNA have a lower impact on the final noise figure.
The amplifier has the purpose of amplifying the signal to a higher amplitude. In the receiver part of a radio system this is extremely important because the signal is often exceptionally weak at the input of the chain.

If the amplitude is not high enough, the ADC in the SDR would not be able to quantise the signal anymore. The gain factor required is dependant on all other components and was determined in section 5.3. Due to non ideal components in the amplifier we can assume that a distortion will occur. Therefore after the amplifier, some kind of noise suppressing component is beneficial, in our case a filter is used.

RF Filter

The purpose of the filter is to suppress undesired parts of the signal. On this point in the chain it suppresses the harmonics introduced in the RF LNA. The harmonics are defined as in equation 5.1.

$$f_h = n * f_c \tag{5.1}$$

With:
f_h: the frequency of the harmonics [Hz]
n: an arbitrary number, 1,2,...,∞

The RF filter lowers the amplitude of the harmonics. The best filter to use here is a narrow-band band-pass filter, this will suppress unwanted signals that may be picked up by the antenna.

Mixer

The mixer is utilised to lower the centre frequency of the signal, the way to achieve this is to combine 2 different signals, and the resulting signal will have a few frequency components. These frequency components are defined according to the combination of the 2 signals, the mathematical representation is shown in 5.2.

$$f_{if} = |n \cdot f_{rf} \pm m \cdot f_{lo}| \tag{5.2}$$

With:
m=0,1,...,∞: this ranges from 0 -> ∞
n=0,1,...,∞: this ranges from 0 -> ∞
f_{if}: the intermediate frequency [Hz]
f_{rf}: the frequency of the radio signal [Hz]
f_{lo}: the frequency of the local oscillator [Hz]

For our setup, the $f_{rf} - f_{lo}$ is the component of the signal that we wish to use. To use this effectively, a filter follows the mixer to suppress the unwanted frequency components, leaving only the desired centre frequency.
The requirements for the mixer to function correctly, is that the LO driver signal, which is mixed with the RF input signal, has as requirement that it needs a higher power on the LO line than on the RF signal line.

Local Oscillator

The requirements for the local oscillator have been highlighted in the Mixer section. These are primarily the frequency and the driving power. The driving power needs to be sufficient for the mixer to function correctly, and the frequency is determined on basis of equation 5.2.

5.2.2 Intermediate Frequency Part

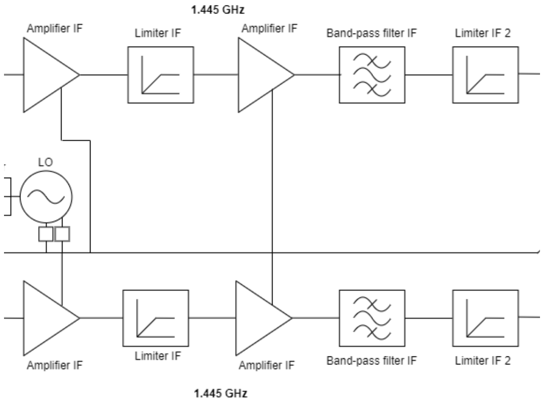


Figure 5.5: Proposed chain for the IF part of the system

In the intermediate frequency part, the chain is defined as the part which has a centre frequency of 1.445 GHz. These are the IF amplifiers 1, the IF limiter 1, the IF amplifier 2, the IF band-pass filter and the IF limiter 2.
These components are shortly discussed as to why they are used and their main properties.

IF Amplifier 1

The amplifier is utilised to provide the required gain to connect the dynamic range of the input to the dynamic range of the SDR, to be able to correctly receive the minimum signal we wish to receive.

IF Limiter 1

This limiter is used to protect the second IF amplifier, the first IF amplifier does not require a limiter because the RF limiter already fulfills this purpose. The total gain between the RF limiter and the IF amplifier 1 is sufficient to not exceed the maximum power limit.

IF Amplifier 2

Similarly as IF amplifier 1, the amplifier is utilised to provide the required gain to connect the dynamic range of the input to the dynamic range of the SDR, to be able to correctly receive the minimum signal we wish to receive.

IFFfilter

The IF filter limits the bandwidth of the noise in the receiver chain. The position of the IF filter is after the mixer, because the mixer moves the centre frequency onto the IF frequency. This property introduces extra frequency components in the signal on the harmonics of the local oscillator frequency. These frequency components need to be suppressed, and the IF filter fulfills this purpose. A narrow band-pass filter that just about encompasses the full bandwidth surrounding the centre frequency is desirable.

IF Limiter 2

This limiter is placed just prior to the SDR to protect the SDR from possible power surges that exceed the maximum power input of the SDR.

5.3 Receiver Requirements

The chain (figure 5.1) incorporates the minimum and maximum transferred power. The main factors taken into considerations were the dynamic range and the required gain. The values for these properties have changed heavily during the course of the project.

5.3.1 Frequency

The first requirement which we need to think about is the frequency of the signal. To lower the noise power the best thing is to get a narrow-band filter which is slightly larger than the bandwidth of the signal. But due to the Doppler shift, the filter might be too narrow-band. From equation 3.6 it follows that you can find the difference in frequency due to the difference in velocity of the objects.
Expecting V to have a maximum of around 65 m/s, the cruise speed of a Cessna 172, the Doppler shift would be equal to about 4 MHz. This can become twice as large if speed of transmitter/receiver is also taken into account, so a maximum frequency difference of 8 MHz. For the tune range of the SDR, this would not matter at all. For the filter however this can be problematic for a narrow-band filter with the exact bandwidth of the signal to be received.
The selected filter should be able to handle a 10 MHz shift to high or low region, given that the LO is appropriately chosen. This will be used in section 6.5.

For the IF frequency, if a high frequency is used, the losses will be higher in the cables, but in base-band an extra DC noise component is introduced as well. Therefore we opted that the most optimal centre frequency is situated between 0.5 and 2 GHz.

5.3.2 Dynamic Range

Operating conditions

Some cases of operating condition should be defined beforehand.

- Accidents
  This range is used for extreme powers possibly transmitted through the device, the limiters will be based upon these values.
  This would be defined as 1m range with the system's own signal with a direct path.
- Consistent operating
  The range at which the gain is sufficient to coherently receive and decipher the signal in the SDR.
  This would be upwards of 305.6 m range.

Dynamic Range

The dynamic range of the system is very important, it defines the maximum characteristics of the system. This is defined on the SDR side by the amount of bits and it is defined on the antenna side by the minimum and maximum power it receives. The current SDR has 12 bits range for the quantization, this is used to

calculate the dynamic range of the SDR, $D_{SDR} = 20 \times \log(2^Q)$=72.24 dB.
The dynamic range of the receiver chain should be contained within the dynamic range of the SDR. If it cannot be contained within, a variable gain amplifier should be utilised.
For the minimum receiver power, the radar range equation (3.2) will be utilised with the minimum RCS.

For the maximum received power a formula is utilised that uses the gain from the antenna, the transmitted power and the FSPL. Equation 5.3 shows the equation.

$$P_{r_{max}} = \frac{G_r \cdot G_t \cdot P_T}{FSPL} \tag{5.3}$$

With:
$P_{r_{max}}$: minimum power in the antenna [dBm]

The way these equations will be used is to determine what power will be received at the output of the antenna on the defined ranges. The dynamic range is defined according to equation 3.3.
As defined in the section covering ranges: 1000 feet separation will be used for the minimum distance between transmitter and receiver which equates to 304.8 m.
For the minimum power is determined to be the least required SNR to coherently detect a signal.
These values combined equates to a dynamic range of 59.5 dB. This value is within the value for the dynamic range of the SDR.

A plot has been made that shows 3 levels of power in the chain, minimum, maximum and accidental, and shows how these powers change due to the components in the chain. These power levels are defined as the powers at the input of the chain. The plot can be seen in the appendix in figure A.7.

5.3.3 Gain

A main point in the design requirements is the gain, it should be sufficient to quantisise the least signal. To do this the following equation has been made;

$$G_{req} = \frac{P_{min_{in}}}{P_{min_{out}}} \tag{5.4}$$

With:
G_{req}: required gain for min of input to min of SDR
$P_{min_{in}}$: minimum power in the antenna [W]
$P_{min_{out}}$: minimum power in the SDR [W]

$P_{min_{in}}$ is defined according to the minimum power which can still be recovered above the noise. This can be seen through the SNR. If remains below a certain threshold after the chain it cannot be recovered, this is defined according to 10 dB after matched filtering.

For the minimum power at the SDR side we used the maximum input peak power and subtracted the dynamic range of the SDR.

$$P_{min_{out}} = P_{max_{sdr}} - D_{SDR} \tag{5.5}$$

With:
$P_{max_{sdr}}$: maximum power in the SDR [dBm]
D_{SDR}: dynamic range of the SDR [dB]

For the total gain required we introduced the losses that are introduced in the chain.

$$G_{total} = G_{req} - L \tag{5.6}$$

With:
G_{total}: total required gain [dB]
L: the losses in the chain [dB]

The total required gain (G_{total}) equates to 39.7 dB, this can be achieved with 2 or 3 amplification stages, both options will be looked at. The code which was used to calculate these values can be found in the appendix (B.1).
Because the dynamic range of the SDR exceeds the dynamic range of the input with more than 10 dB we chose to increase the amplification by 10 dB to make the signals with the least power better visible.

5.4 Calibration

The two receiver chains connected to the SDR do not generate the exact same outputs due to difference in component manufacturing or assembling for example. This can be done with a one-shot calibration, where by doing simple tests the differences can be found, and in the SDR an adjustment can be utilised to remove the differences between the different chains.
Apart from balancing the different chains, an extra tuning voltage is required to control the LO, this voltage will need an adjustment due to possible manufacturing problems. Therefor using a calibration for this part will be required to get the exact required tuning voltage.

Chapter 6

Component Discussion

6.1 General

The goal of this chapter is to discuss the reasons for picking specific components, this is in the shape of defining requirements for specific components, then discussing the possibilities and finishing with the chosen components.

6.2 Antenna

The different options that we considered were a trade-off between directivity, gain and cost and size.
The actual implementation of the antenna is not required for the workings of the chain, a valid approximation will be utilised that could be implemented from the perspective of a filter and a similar gain for in the radar range equation.
Designing the actual patch antenna is outside the scope of this thesis and therefore a recommendation of characteristics is discussed. The requirements in question can be found in section 5.2.
These requirements concern the gain, centre frequency and size. For the gain, we looked at several different real life implementations and design procedures, and made an assumption for the gain. The assumption expects a 3-8 dBi gain as min and max in the angles which we will use. This assumption was used in the calculations for the gain and dynamic range.
The centre frequency is primarily dependent on the size of the device, which follow stringent constraints that can be found in [17]. These size constraints can be used for the design, since the size is just smaller than the size required for the algorithm.

6.3 Low Noise Amplifier

The purpose of the LNA is to provide enough gain to make sure that the ADC can coherently digitize the provided signal. This must be done while keeping the maximum received power with the gain within the limitations of the hardware following the LNA.
The total gain required will be achieved within 3 stages of amplification, one in the RF part of the chain and two in the IF part of the chain. The RF amplifier is an LNA because it should limit the noise addition as much as possible. The IF amplifiers have less severe requirements due to their position in the chain, both less important for noise addition and requiring a easier frequency.

6.3.1 Gain Requirements

We calculated the gain required as in 5.6, this was then used to determine the required gain levels of the multiple amplifiers. It was apparent that the gain should be at least divided into 2 parts, 1 before the mixer and 1 after.
After the mixer the required gain can be achieved in 1 or 2 amplifier stages, the combined gain should be equal to the value defined in the gain chapter. With a gain of about 20 dB in the RF part, another 20-30 dB gain is required in the IF part. This is a large amount of gain for 1 amplifier, therefor 2 possibilities are discussed, 1 or 2 stages in the IF part. The choices for the amplifiers are defined in table 6.1. For 2 stages of amplification, an extra limiter is required in between the 2 stages.

Table 6.1: Specifications for choices for the amplifiers

	Frequency [GHz]	Gain [dB]	Noise figure [dB]	Max P_{in} [dBm]	Price
RF frequency - 9.7 GHz					
ZX60-05113LN+	5-11	20.3	1.7	17	$180
ZX60-06183LN+	6-18	26.2	2	17	$240
ZX60-123LN-S+	0.5-12	16.2	2.4	8	$195
IF frequency - 1.445 GHz					
1 stage					
ZRL-2400LN+	1-2.4	31.3	0.7	10	$140
ZHL-1217MLN+	1.2-1,7	29	1.5	0	$295
2 stages					
ZX60-P33ULN+	0.4-3	14.5	0.5	14	$94
ZX60-P105LN+	0.05-3	14.4	2.0	17	$70
ZX60-33LNR-S+	0.05-3	16	1.0	13	$90

Gains denoted with no.1/no.2 define 2 different gain values for different DC input power for the amplifier. The values in the table are taken for the frequency defined for the RF/IF band.

Our setup consists of:

- RF: ZX60-05113LN+
- IF1: ZX60-33LNR-S+
- IF2: ZX60-P105LN+

This will result in a total gain of 50.7 dB. The first amplifier is chosen because it has the lowest noise figure, the noise figure of the RF LNA is the most important noise figure in the chain. The 2 IF amplifiers are chosen because the combined gain is exactly the amount of gain required.
For the regular operations the limiters will remain unused, they are used to protect the amplifiers if any high amplitude signal enters the device, but the regular signal has an amplitude which is low enough to not require the use of any limiters. The accidental case and the use of the limiters can be seen in figure A.8.

6.4 Variable Attenuator

To combine the total required dynamic range for the chain and the total available dynamic range in the SDR a variable attenuator can be used. The purpose of the attenuator is to provide a small amount of loss when high power is available. The point at which the loss is required is determined on basis of the chain.

The combination of these 2 effects makes sure that the full dynamic range of the input of the chain is reduced somewhat to fit it to the dynamic range of the chain.
This components may be required due to the high dynamic range which is required for the specifications of the chain. The voltage variable attenuator is a suitable attenuator for our purpose, it changes attenuation based on a tuning voltage. This tuning voltage can be derived from the original with a small circuit.
For the current state of our chain, a variable attenuator is not required.

6.5 Filters

The filters are, as specified in chapter 5, required to suppress harmonics of the signal, these are determined through the components which induce them. The main components which induce these signals in this chain are the amplifiers and the mixer. The amplifier has harmonics on $n * f_c$ and the mixer has harmonics on $|m * f_c \pm n * f_{lo}|$. For the amplifiers, a low-pass filter can be utilised to reduce the harmonics, for the mixer however a band-pass filter is required to filter the harmonics due to the high amount of harmonics, both higher and lower. In the datasheet of the mixer in question, the amplitude of the different harmonics is shown.

6.5.1 RF Filter

The purpose of the RF filter, which is situated after the RF amplifier, is to filter out the harmonics induced in said amplifier and to suppress possible unwanted signals from the antenna. To satisfy the first requirement of the filter it has to filter out the frequency above the f_c and lower than $2 * f_c$. To satisfy the second requirement, it needs to have a narrow-band band-pas filter surrounding the centre frequency.
The requirements around the low and high pass frequency are more relaxed than for the IF filter. This is primarily because the IF filter determines the noise bandwidth.
The choices which had been considered were extremely expensive, and instead the option of self designing a filter around our designated centre frequency has been considered.
For this purpose recommendations have been made. These are, having a cut-off frequency around 25 to 200 MHz above and below the centre frequency of 9.7 GHz and an impedance of 50 Ω.

6.5.2 IF Filter

The band-pass filter has been selected to have a narrow bandwidth with the lowest possible noise. For the lowest amount of noise, the bandwidth should be as small as possible. In the requirement section of chapter 5.3, the Doppler frequency shift was used to determine that the bandwidth of this band-pass requires an additional 8MHz. With a bandwidth of 15MHz for the signal itself, some edges to take into account and the Doppler shift, we have opted for a bandwidth requirement of 50MHz for the bandwidth of the band-pass filter.
The centre frequency had to be between 0.5 and 4GHz. The requirements have been set for the range of the SDR and the problems encountered on high frequencies and around DC. This results in a frequency which we have selected to be between 1 and 2GHz.
The choice which has been made for the IF filter is the VBF-1445+, it has a frequency range of 1420 till 1470 MHz.

6.6 Down-converter

The purpose of the down-converter circuit is to lower the centre frequency, this is achieved by using a mixer and a local oscillator with a band-pass filter after the mixer. The mixer combines the incoming signal with the signal from the local oscillator. The output of the mixer has a few different frequency components from the combination of the original signal and local oscillator signal. The band-pass lowers the amplitude of the higher harmonics and only the wanted frequency component remains.
With an input frequency of 9.7GHz and with the goal of an output frequency below 4GHz, we need to apply a f_{lo} of more than 6GHz.

To utilise the SDR for the down-conversion, the agile transceiver, which is utilised in the SDR for tuning to frequencies, should have specifications sufficient for that purpose. It can only reach up to a max of 6 GHz. This gives rise to performance problems at the receiver part of the transceiver. At high tuning frequency and multiple channels used, the bandwidth is extremely limited, this is reduced if only 1 channel is used for the IF signal, which can be split to the 2 mixers. The SDR can only utilise 5 MHz of bandwidth when it is operating with a high tuning frequency. Therefor we opted to get a separate local oscillator.

6.6.1 Mixer

For the mixer the specifications were focused on a low insertion loss, a low requirement for LO power and frequency ranges which were sufficient for our purpose. The choice for the mixer is been MM1-0212LCH-2. The mixer spur can be seen in figure 6.1, it shows an excellent response.

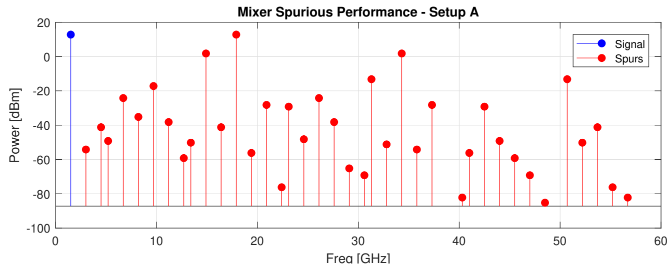


Figure 6.1: The spurious performance of the mixer

This mixer will not be saturated under any scenario in which the design will be used, this can be gleaned from figure A.7, the highest power that is transmitted through the port is -20 dBm, this is severely lower than it is able to handle. The limit for the LO signal in the mixer is between +1 and +15 dBm, the chosen LO provides 20 dB and the splitter lowers this with 3.3-3.8 dB.
This shows that an additional loss of about 2 dB is required to operate correctly. This can be achieved using an attenuator, a fixed attenuator is sufficient. This change has been made and is shown in figure 6.2.

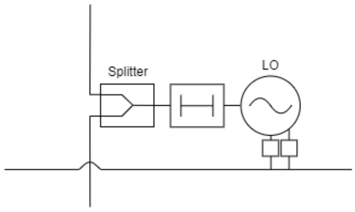


Figure 6.2: Changed setup

The chosen attenuator is the FW-5+, it provides an attenuation of 5 dB and works on the required frequency. It also provides a good flatness for the attenuation across the frequency it is being used in.
For proper operation, the RF signal should not exceed the LO signal in power. As can be seen in figure A.7, the maximum power in proper operation on this part of the chain is about -20 dB this is far below the threshold.

6.6.2 Local Oscillator

The local oscillator needs to produce a steady signal with a steady frequency, these are then combined in the mixer with the RF signal. The output of this mixer will contain several different frequency components. These are filtered with a narrow-band filter so only the desired part of the signal remains.

The LO needs to be appropriately chosen so that the IF frequency is on the desired centre frequency. This equals to the centre frequency of the IF filter. Therefor equation 5.2 is used to calculate the frequency. The $f_{rf} - f_{lo}$ part is the frequency we are interested in. This equates to $f_{lo} = f_{rf} - f_{if} = 9.7 - 1.445 = 8.255$ GHz.

Table 6.2: Specifications for choices for the local oscillator

	f [GHz]	V_{dc} [V]	P_{out} [dBm]	f_{use} [GHz]	V_{tune} [V]	Second harmonic [dBc]
HMC-C200	8-8.3	6.5-15	13	8.2	-	-28
HMC-C030	8-12	12	21	8.2	0.9	-20
HMC-C029	5-10	12	20	8.2	10	-15

The choice which has been made is the HMC-C029, this component is connectorised, so will be easy to implement in the design. Apart from that the specifications are sufficient for our goal. It does have a power supply requirements of 12V, this will require or a transformer from 5 -> 12V, or an extra power supply on 12V.

6.7 Limiters

The limiters should protect the sensitive components from harm, to determine the levels at which the limiters should stop, the specifications of these sensitive components should be utilised and the maximum possible power input.

$$P_{max} > P_{limiter} \times G \tag{6.1}$$

With G being the gain between the limiter and the component in question.
While designing, an estimation was made on where limiters were required. The sensitive components in

question were the amplifiers and the SDR. For passive components problems would only occur if the power exceeds 1W for most components, this is 30 dBm. Limiters are primarily used for this limit, because these contain the problem the high power poses.
There are 3 amplifiers and 1 SDR in the design, therefor at most 4 places are used to place limiters, in front of the sensitive components.

Table 6.3: Components with max powers for choosing limiter position and power

Component	Max power [dBm]
RF LNA	17
Mixer	30 (1 for proper operation)
IF LNA 1	13
IF LNA 2	16
SDR	2.5

On basis of the previous table (6.3), figure A.7 and the link budget (A.3 and A.4), which shows the maximum possible power throughout the chain, the position and values for the limiters can be chosen.
The limiters which were found seem to have a max power around 30 dBm, this can impose a limit in a chain with almost 50 dB gain.
The SDR has a max power it can contain of 2.5 dBm, the limiter needs to be between the last RF amplifier and the SDR. Due to the limit of 30 dBm, an extra limiter is required between the 2 amplifiers, this can be seen in figure A.8, without a second limiter the final limiter will not function.
A last limiter was added at the front of the chain, this has been done primarily for unknown values, as a surrogate the direct signal was taken on a very close range, 1 m. It increases the highest possible power it can handle. It could be omitted, but it was retained for the increased safety. The following table (6.4) shows the choices we considered for the different limiters.

Table 6.4: Specifications for choices for limiters

	f [GHz]	Insertion Loss [dB]	P_{out} [dBm]	$P_{in_{min}}$ [dBm]	$P_{in_{max}}$ [dBm]	Price
IF Limiter 1 - Pre RF Amplifier 2						
ZFLM-252-1WL-S+	0.1-2.5	0.6	0	+5	+32	$57
VLM-83-2W-S+	0.03-8	0.4	+11.5	+12	+32	$62
VLM-73-1W-S+	0.03-7	0.2	+11.5	+12	+30	$52
IF Limiter 2 - Pre SDR						
ZFLM-252-1WL-S+	0.1-2.5	0.6	0	+5	+32	$57

Notes: VLM-73-1W-S+ is unsteady on the required frequency, with higher input powers the output power is lowered.
For the high frequency limiter no acceptable device has been found.

The use of theses limiters can be seen in figure A.8. It can be seen that the level is exceeded and the limiter brings it back down.

6.8 Secondary Components

6.8.1 Power Supply

The power supply is assumed to produce a steady 5V with a current that is enough to power all the different connected components. These include the SDR, amplifiers and the local oscillator.
For the components which require a different voltage, a transformer is utilised. This is represented in the design in the form of a small box without any description, and it is assumed that this box produces the required voltage.

6.8.2 Splitter

The splitter requirement pertains mainly to the frequency at which the local oscillator produces a signal. The second requirements is that it should be able to withstand the power that the local oscillator produces, which is 20 dBm and equates to 0.1 W.

Table 6.5: Specifications for choices for the splitter

	Frequency [GHz]	Insertion loss [dB]	Isolation [dB]	P_{max} [W]	Price
ZFRSC-123-S+	0-12	9.5	19.5	0.16	$75
ZFRSC-183-S+	0-18	6.7-7.25	6.2	0.16	$90
ZX10-2-98-S+	4.75-9.8	3.3-3.8	31	1	$40

Splitters split the signal into multiple outputs, therefor they already have losses depending on the amount of outputs. This was taken into account and added to the insertion loss.
Our choice is the ZX10-2-98-S+.

6.9 Analysis

Provide information on the impact that each component has, with the choices. The basis analysis has been done with link budget analysis, the link budgets in question can be found in A.3 and A.4.
These link budget show some design properties and how all components introduced alter the properties of the signal.

6.9.1 Gain Analysis

To determine if the gain will be functioning correctly, code was written with the data provided about the chain. This test can be seen in figure A.7.
It shows the power after each components, for 3 possible input powers. These powers are the least and most power expected from regular use of the device, and the power which comes from the accidental max power on the device. This test is used as an indication to see where limiters are required.
Another test was made to show how the signal power changes over distance, this can be seen in figure A.5 and in figure A.6.
For the least amount of power, the noise floor was utilised, the final goal with which to work with at the algorithm side was an SNR of 10 dB. With the gain introduced by the post processing in the matched filter, the required SNR is equal to the noise floor. This value can be used to check if a signal will still be usable in the SDR.
This figure can be used to see the the maximum distance at which the setup can be used.

6.9.2 Limiter Analysis

To determine if the limiters will be functioning correctly, code was written with the data provided about the chain. This test can be seen in figure A.8.
The figure shows possible scenarios involving 0-3 limiters, it shows the total power after each component. The input is taken as the highest possible power, this is the accidental power as input. The different cases are from the amount of limiters used in the design. It can be deduced that all 3 limiters in the design are necessary.

Chapter 7

Algorithm

7.1 Angle of Arrival

The Angle of arrival is the angle between the receiver and the incoming echo signal. This can be calculated with differing methods. This thesis focuses on using the classical method, Fast Fourier Transform (FFT) with information taken from [18].

7.1.1 Uniform Linear Array

The classical method used in this thesis makes use of the difference in arrival times at the uniformly linearly spaced Array (ULA) 7.1. This setup allows for some conveniences in setting up the steering vector discussed later on.

To prevent the antennae from aliasing a maximum distance between the two antennae is established [19].

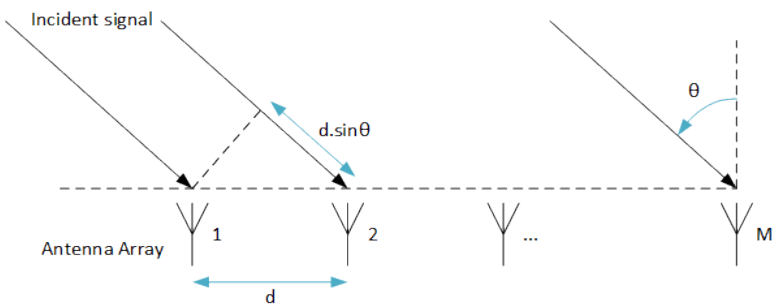


Figure 7.1: Uniformly Linearly Array with multiple receiving antennas

The maximum distance between these antennae is defined as 7.1.

$$d_{max} = \frac{\lambda}{2} \tag{7.1}$$

The time light takes to reach the antenna from another the first antenna is defined in 7.2

$$\delta_t = \frac{(n-1)d}{c} \tag{7.2}$$

7.1.2 Narrow-band

A few assumptions have to be made in order to use this method, namely that the system is narrowband. The system operates in narrowband if the equation 7.3 holds.

$$B \cdot \delta_t = \frac{(n-1)d}{c} \ll 1 \tag{7.3}$$

With:
n = 1, . . . , N: number of the sensor
δ_t: time delay between antennae [m]
d: distance between elements [m]
B: bandwidth [Hz]

If equation 7.3 holds then the signal is in narrowband and the incoming signals should differ very little in power between the receivers.
The maximum delay in arrival time between sensors is defined as in equation 7.4.

$$\delta_{t_{max}} = \frac{(n-1)(d \cdot \sin(\theta))}{c} \tag{7.4}$$

With:
θ: the angle of arrival [rad]

7.1.3 Signal Model

When the received signal at each receiver is assumed to be a far field signal, the signal at each receiver becomes parallel to each other. Therefore only a time delay τ_n between the receivers will occur [20].

$$r_n(t) = s(t - \tau_n)e^{-j2\pi f_c \tau_n} \tag{7.5}$$

$$s(t - \tau_n) = \int_{\frac{-\Delta F}{2}}^{\frac{\Delta F}{2}} S(f)e^{-j2\pi f_c \tau_n} e^{-j2\pi f_c t} \tag{7.6}$$

With:
f_c: carrier frequency [Hz]
τ_n: time delay [rad]

Using the Fourier transform on equation 7.5 shows in 7.6 that when the narrowband assumption is satisfied,

$$2\pi f \tau_n \ll 1 \text{ and } e^{-j2\pi f_c \tau_n} \approx 1 \tag{7.7}$$

$$s(t - \tau_n) \approx s(t) \text{ and } r(t) \approx s(t)e^{-j2\pi f_c \tau_n} \tag{7.8}$$

the exponent as seen in 7.7 goes to 1 and therefore the delay in time between the arrival across the receivers results purely in a phase shift as seen in equation 7.8.
Since the narrowband assumption is satisfied the delay in time becomes a delay in phase and this phases delay is defined as 7.9

$$\tau_n = \frac{2\pi(n-1)d\sin(\theta)}{\lambda} \tag{7.9}$$

with:
n = 1, . . . , N: number of the sensor
d: distance between elements [m]
θ: the angle of arrival [rad]
λ: wavelength [m]

7.1.4 Steering Vector

Combining the received signal $r(t)$ and the phase delay between the elements, as seen in 7.10, allows us to construct a steering vector where each row differs in N.

$$r(t) = s(t)e^{-j2\pi(n-1)d\sin(\theta)/\lambda} \tag{7.10}$$

$$\begin{bmatrix} r_0(t) \\ r_1(t) \\ \vdots \\ r_{N-1}(t) \end{bmatrix} = \begin{bmatrix} 1 \\ e^{-j2\pi d\sin(\theta)/\lambda} \\ \vdots \\ e^{-j2\pi(N-1)d\sin(\theta)/\lambda} \end{bmatrix} s(t) \tag{7.11}$$

7.1.5 Matched filter

A matched filter, as seen in 7.12, is a filter that does a convolution on a signal with its time-reverse conjugate to achieve the recovery of the original signal, to give an indication of the most likely spot in a small time frame, of where the signal is.

$$y[n] = \sum_{m=-\infty}^{\infty} x[m]x[-(n-m)]^H \tag{7.12}$$

This is desirable because we work with very low voltages, and without the maximum SNR we will not be able to recover the original signal.

7.1.6 Fourier Transform

After match filtering the signal and maximizing the SNR the signal transformed using the FFT over the antennae in order to isolate the $\sin(\theta)$ component of the incoming signal. The highest value in the matrix is then assumed to be the incoming angle if the axis is defined as $\sin(\theta)$.

7.2 Design of Algorithm

The design of the algorithm started by figuring out how the incoming signal would arrive at the SDR. Assuming that the signal form itself has not been altered by the components in the receiver chain, this signal would have the same form as the signal that arrived at the receiver itself.

7.2.1 FFT

With the now demodulated signals a FFT is applied and the result is shifted to the centre. Since the result will be in the form of $\sin(\theta)$ the results will be measured transformed to the arc sinus of the thought to be result.

7.2.2 Tracking

A negative feedback loop is applied that us the previous value to adjust the new value of the estimated angle. This loop is used to primitively track the signal. This stabilizes the estimated angle as our two channel estimation itself is prone to small estimations errors.
The tracking has another benefit that it allows us to ignore values that exceed the previous value by a too large of a margin. These values are assumed to be faulty in the calculation and the previous value is assumed.
A downside of this form of tracking is that when the object actually changes significantly in angle the tracking mechanism will reject this change as it is assumed as an error. This problem is solved by counting the times the algorithm hits this significantly different value, when the result of the script is back to back significantly different than its previous value the tracking algorithm decides this new value is the actual value and continues from this point on wards.

Chapter 8

AoA Simulation

In this chapter we will discuss some simulations which were made with various programs with various purposes.

8.1 Preparation

The would be incoming signal has to be simulated in MATLAB during the simulations. The incoming signal is simulated as in 8.1

$$r(t) = e^{j\pi k \odot (t-\tau).^2 - 2j\pi f_c \tau} \tag{8.1}$$

With:
k: B/T [$\mathrm{Hz\,s^{-1}}$]
B: bandwidth [Hz]
T: pulse width [s]

An ULA as seen in 8.2 is also required to be made as it simulates the different phase delays for each antenna. The ULA will be defined as a matrix with an exponential that simulates this delay.

$$a(t) = \begin{bmatrix} 1 \\ e^{2j\pi d \sin(\theta)/\lambda} \\ \vdots \\ e^{2j\pi(N-1)d\sin(\theta)/\lambda} \end{bmatrix} \tag{8.2}$$

These two components are then added together and used as the noise free signal input. The would be noise is then added as white Gaussian noise, and normalized according to the predefined input SNR. A matched filter 8.3 is then used to demodulate the signal and maximize the SNR.

$$dm[n] = \sum_{m=0}^{T} e^{j\pi kt[m]^2} e^{-j\pi kt[-(n-m)]}; \tag{8.3}$$

With:
T: Total sample size

8.2 Simulations

With the simulations we tested and showed the effectiveness of the different parts of the AoA script.
The first simulation tests the effectiveness of the two sensor ULA, against a more advanced four or even eight sensor ULA.
In the second simulation we have tested the entire script overall, and more specific the tracking capabilities of our algorithm.

8.2.1 Different Array Size

With this simulation we have tested the difference in accuracy with a differing amount of sensor array elements. Since our budget only allows for two sensors this is especially important. For this simulation the SNR was tuned on -5 before the matched filter and the simulated incoming angle was at 30 °. The results are shown in A.10, although the peak of the two elements array is significantly lower and less steep it still clearly shows the peak is at 30°, these results are satisfactory for our purpose.

8.2.2 Time Simulation

In the time simulation we have run a script in a loop as to simulate a time signal. In the loop every operation changes the angle of the incoming signal. During the simulations we have checked if it stayed within the ±4°, which is a 300 meter difference at 5km.
All the simulations used an input SNR of -10 dB before the matched filter and all the graphs from the simulations are in the A.

Simple Sine-wave

As a start the entire code was simulated using a simple sinusoidal wave A.9. The wave varied between ±60° that showed the algorithm staying withing the set boundaries most of the times, although at the peeks it went outside these boundaries multiple times, this in itself is less of a problem as the exact elevation of objects much higher and lower than the drone are not immediate points of collision.

Tracking

The effectiveness of the tracking had to be tested on effectiveness and the necessity of it. A loop with the incoming angle slowly differing around the 0 degrees with and without the feedback loop was tested and checked if the negative feedback loop had a positive impact.
The simulated signal used was in the form of a square wave with ±5° this signal was chosen because it both simulates a steady incoming angle and a sudden change in angle that would test if the negative feedback had any negative impact on a more fast changing object.
As seen in the appendix A.11 the feedback stabilises the signal at the constant angles and changes quickly to the new angle. Without the feedback however the signal bounces out of the requirements.
The final simulation was testing if the algorithm would change to a new angle if the angle changed drastically. A good test for this part of the tracking algorithm is a saw-tooth figure, where steep changes happen. As seen in A.13 the angle drops after 2 calculations at each drop, after which it follows the signal nicely again.

Chapter 9

Discussion and Conclusion

9.1 Discussion

The first things that were decided upon prior to the design phase were the characteristics of the signal, these were primarily preoccupied with the frequency band and bandwidth. This was done because these characteristics form the basis for the design procedure.
After these criteria were selected, the design process started. For the receiver chain, the most important part was the SDR, this would be the basic component for the design, and if no appropriate SDR could be found the design criteria needed to be revised.
The chain was designed with an appropriate SDR, the structure was made to increase the amplitude of a weak signal with minimal distortion. It included a high gain and included noise reducing components. With the requirements that came with the SDR, there needed to be a down-converter circuit and it was realised using a mixer and a local oscillator.
With the general setup thought out, the gain which was required needed to be determined, this was done on basis of the transmitted power from the transmitter group. Due to miscommunications with other groups, this value has changed constantly over the course of the design stages.
The final received power which followed showed that the initial requirements could not be satisfied with the setup. This problem however is inherent to the choices made and the transmitted power used, there is a limit to what can be achieved by reducing noise and providing gain.
From the code an approximation can be made from the maximum range by taking the 4-th root of the $RrRt^2$ product. This results in a range of 42m. This value is low compared to the original goal.

There are ways to enlarge the range, this can be done by increasing the transmitted power or lowering the frequency at which the signal is transmitted. The transmit power and frequency both have the same impact on the range. Our choice to use the x-band has lowered the range considerably.
The original design criteria were unattainable, the ranges were in the kilometer range, while the current setup can at most receive a fraction of that.

The design for the AoA algorithm was decided rather early in the design phase. After a lot of research on multiple AoA algorithms the standard and more simple design of FFT was picked. The basis for this algorithm was written together with our supervisor Faruk Uysal around the 4th week of the BAP. After the initial design finished the AoA part was put on a low fire and the design chain was the focus. Around the time of the Green-light most of the simulations were finished where the design choices were tested and changed if other values were found to be more beneficial.

The problem which was most important in wasting time was miscommunication between all contestants in the project, the communication through digital media is limited to say the least.

After our initial defence this thesis received a fail, and we were given points for improvement. Most of these points of improvements were implemented and additional alterations have been made after meeting with our supervisors.

Future Work

- Instead of using the X-Band for transmission, a lower frequency band can be used, as long as the wavelength has sufficient resolution to be able to detect the required RCS of the target.
- The transmitted power which has been utilised by the system is quite low compared to what is being used in conventional radar systems, enlarging this value can increase the maximum range of the signal.
- For the price range which is given for this design in combination with the requirement of off-the-shelf equipment makes it quite difficult to get acceptable components, changing one of these 2 point can have advantageous effects on the result.
- If in the future the possibility to receive more objects is desired at least double the current amount of antennae are required to receive additional objects at satisfactory accuracy.

9.2 Conclusion

The requirements which were the foundation of this project were not feasible, trying to make the design with those requirements has kept the design going in circles. Finally the requirements were used as a guiding path, and the design was advanced to the stage at which the maximum possibilities were explored instead. This exploration has taken off after the original fail, and considerable improvements have been made.
To conclude, we are of the opinion that the complete project has not succeeded for the company, but we have learned a lot about designing, iterating on said design and improving our own skills of communication and knowledge. During the corona crisis this was especially required, and there have been great strides of improvement.

Appendix A

Images

A.1 Chain

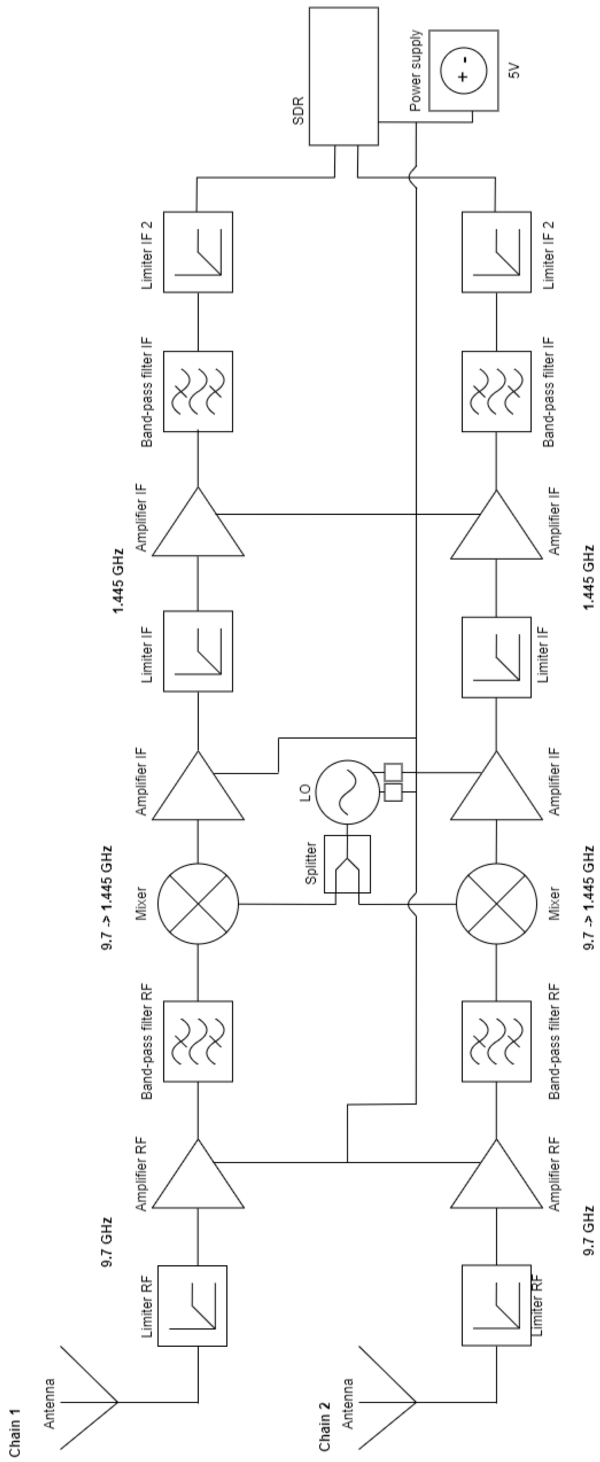


Figure A.1: Full chain

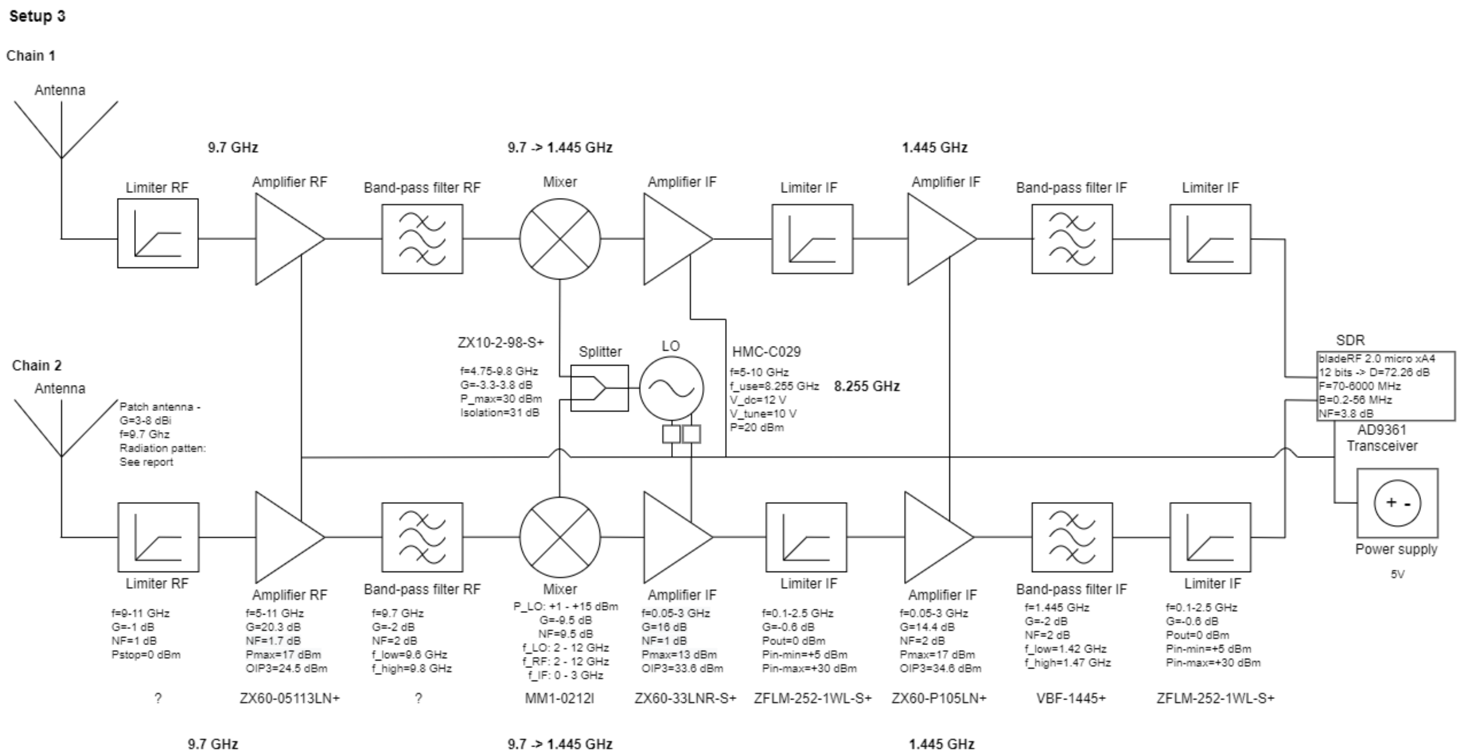


Figure A.2: Full chain with more information

A.2 Link Budget

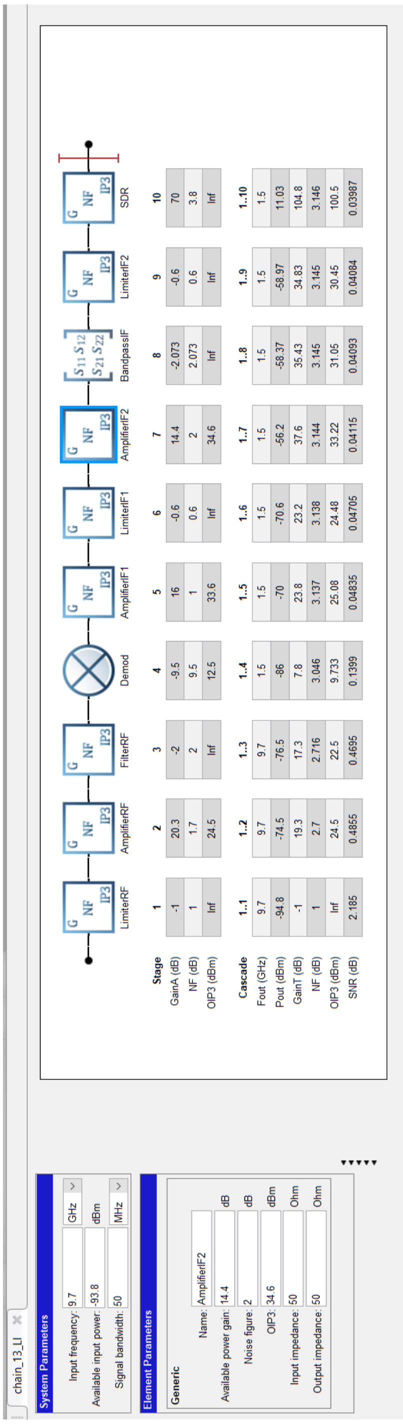


Figure A.3: The link budget of the final component selection

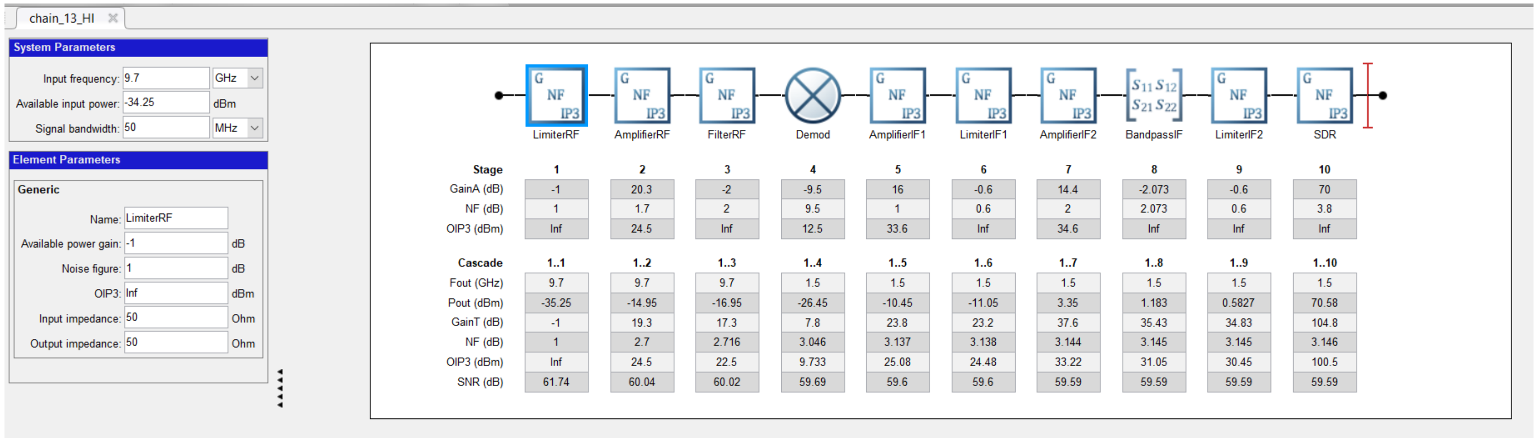


Figure A.4: The link budget of the final component selection

A.3 Analysis

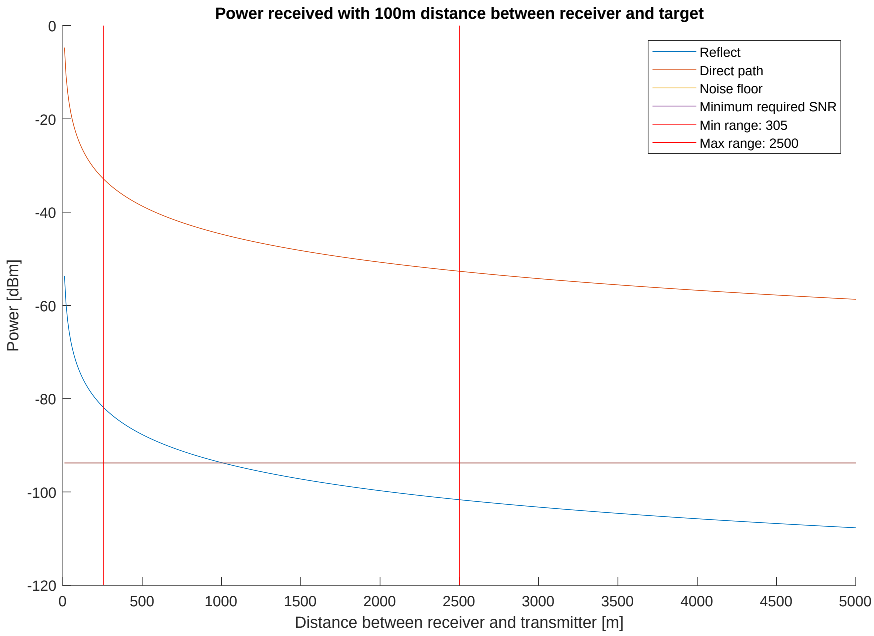


Figure A.5: Figure of powers plotted against ranges

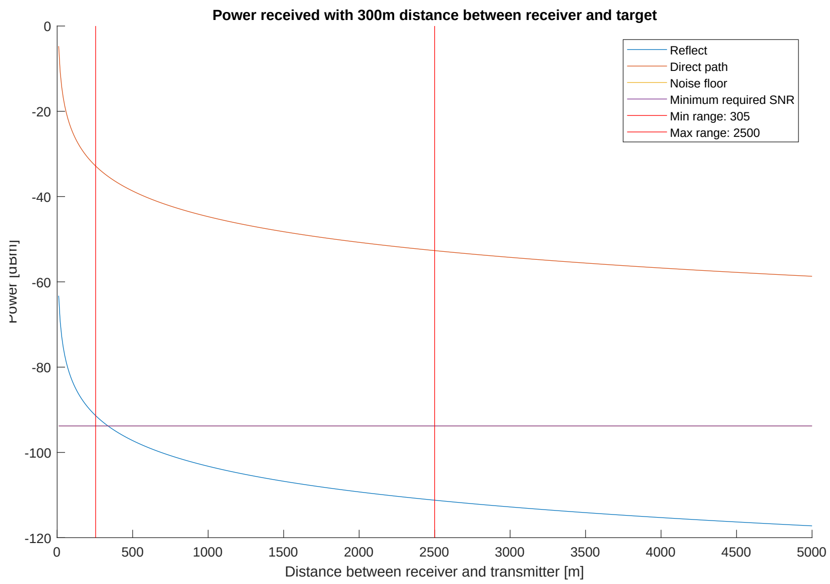


Figure A.6: Figure of powers plotted against ranges

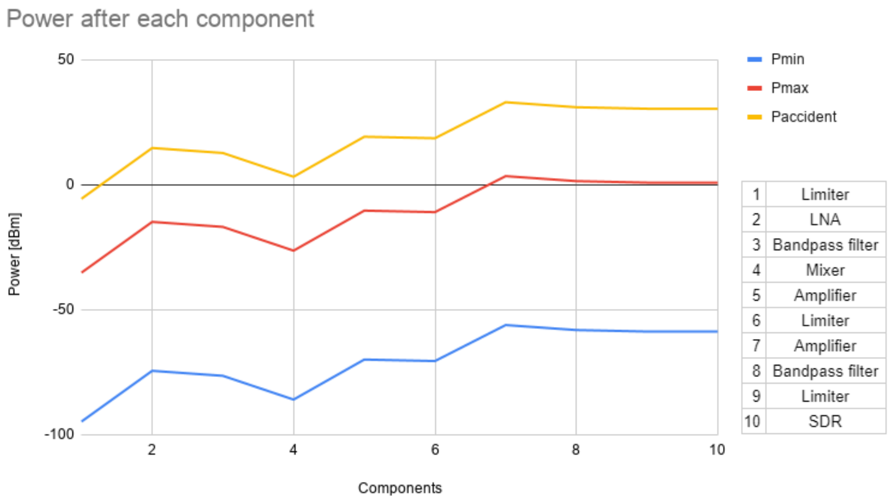


Figure A.7: Gain of multiple devices and impact on chain

Figure A.8: Gain of multiple devices and impact on chain with limiters

A.3.1 Simulation

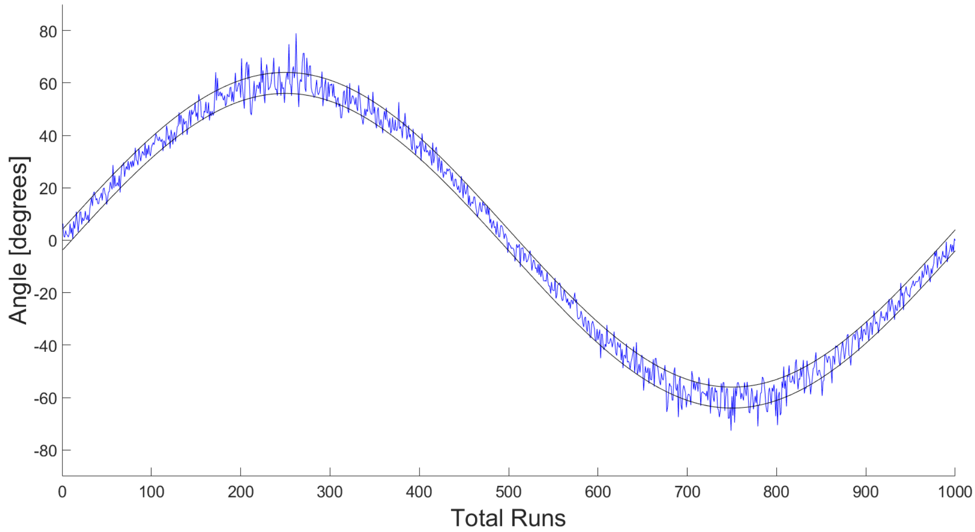


Figure A.9: Simple Sine-wave plotted over multiple runs

A.3.2 Different array size simulation

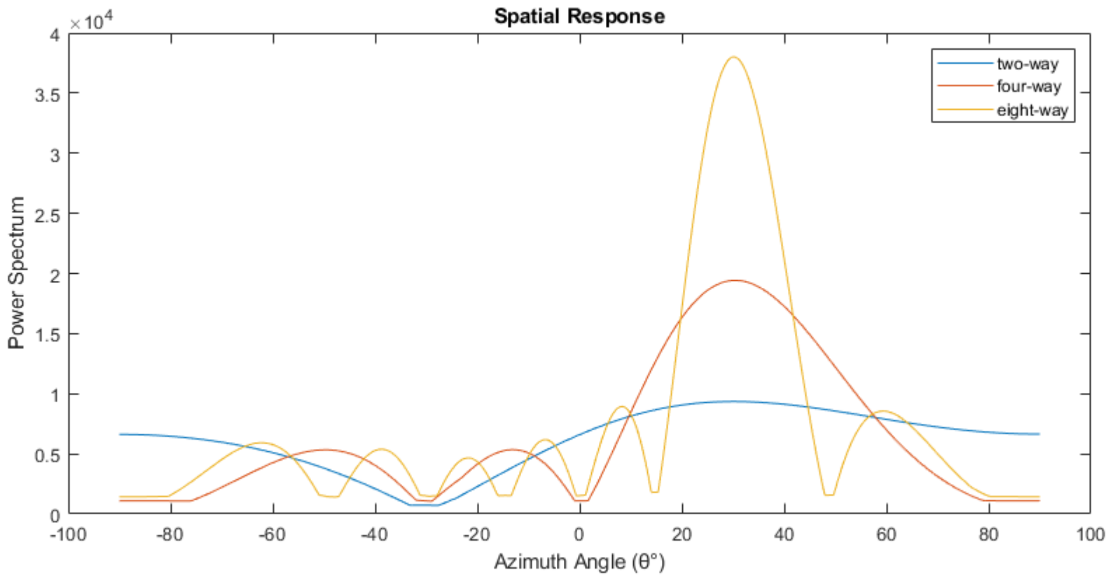


Figure A.10: Spectral response of different chain sizes

A.3.3 Feedback Simulation

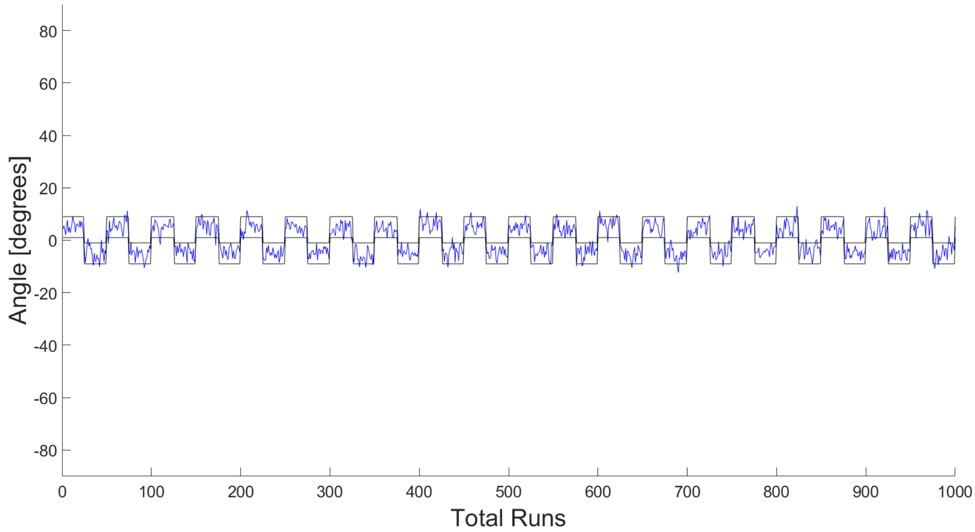


Figure A.11: Signal as a square-wave with feedback

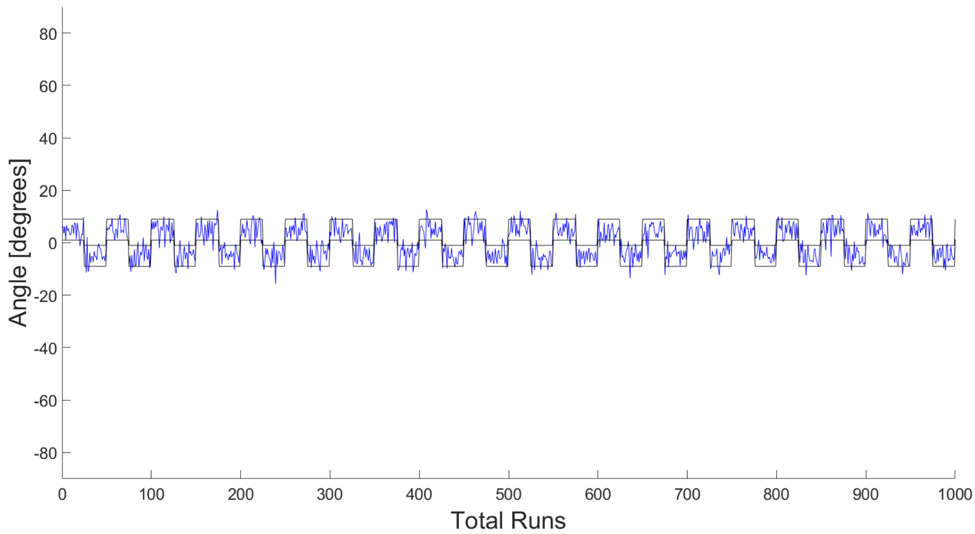


Figure A.12: Signal as a square-wave without feedback

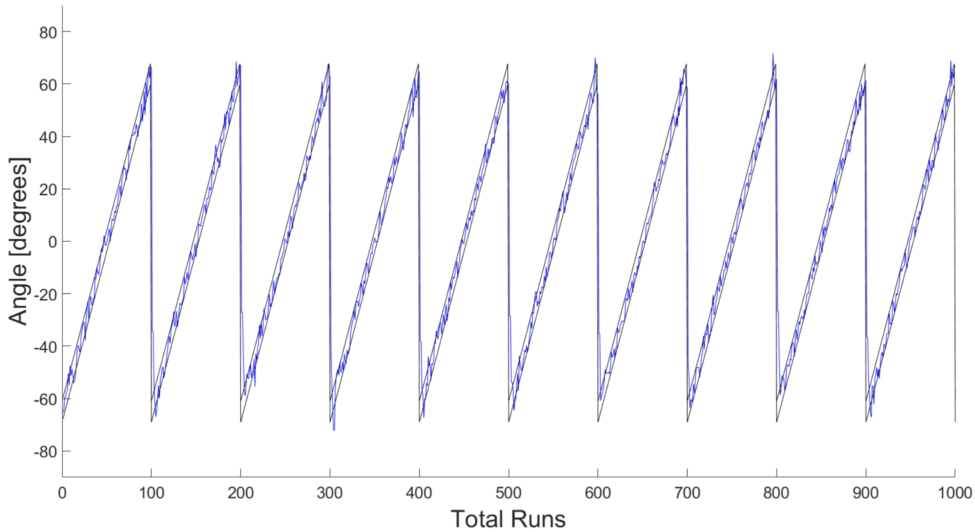


Figure A.13: Sawtooth wave to demonstrate the extremes rejection

A.4 Datasheets

A.4.1 RF LNA

Coaxial

Low Noise Amplifier

ZX60-05113LN+

50Ω 5 to 11 GHz

Generic photo used for illustration purposes only

CASE STYLE: GC957

Connectors	Model
SMA	ZX60-05113LN+

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Features

- Ultra low noise figure, 1.7 dB typ @ 8.5 GHz
- High gain 22 dB typ at 8.5 GHz
- Excellent Gain flatness, ±0.7 dB over 5.0 to 8.5 GHz and 6V

Applications

- Microwave radios
- C-band application
- X-band application
- Instrumentation and lab use

Electrical Specifications at 25°C and 5V, unless noted

Parameter	Condition (GHz)	V_{DD}=5.0			Units
		Min.	Typ.	Max.	
Frequency Range		0.5		11.0	GHz
Noise Figure	5.0-7.0 7.0-9.0 9.0-11.0		2.3 1.8 1.7		dB
Gain	5.0-7.0 7.0-9.0 9.0-11.0	17.5	22.2 21.4 20.1		dB
Input Return Loss	5.0-7.0 7.0-9.0 9.0-11.0		6.7 12.1 9.0		dB
Output Return Loss	5.0-7.0 7.0-9.0 9.0-11.0		13.0 17.0 11.5		dB
Output Power at 1dB Compression (1)	5.0-7.0 7.0-9.0 9.0-11.0		12.4 13.0 13.0		dBm
Output IP3	5.0-7.0 7.0-9.0 9.0-11.0		25.0 24.5 24.0		dBm
Device Operating Voltage (V_{DD})	—	4.9	5.0	9.0	V
Device Operating Current (I_{DD})			42	53	mA

1. Current increases at P1dB
2. OIP3 measured with 0 dBm tones and 1 MHz spacing.

Notes
A. Performance and quality attributes and conditions not expressly stated in this specification document are intended to be excluded and do not form a part of this specification document.
B. Electrical specifications and performance data contained in this specification document are based on Mini-Circuit's applicable established test performance criteria and measurement instructions.
C. The parts covered by this specification document are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, "Standard Terms"); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp

A.4.2 Mixer

3. Specifications

3.1 Absolute Maximum Ratings

The Absolute Maximum Ratings indicate limits beyond which damage may occur to the device. If these limits are exceeded, the device may be inoperable or have a reduced lifetime.

Parameter	Maximum Rating	Units
Port 1 DC Current	30	mA
Port 2 DC Current	30	mA
Power Handling, at any Port	+30	dBm
Operating Temperature	-55 to +100	°C
Storage Temperature	-65 to +125	°C

3.2 Package Information

Parameter	Details	Rating
ESD	Human Body Model (HBM), per MIL-STD-750, Method 1020	1A
Weight	S Package	10 g

3.3 Recommended Operating Conditions

The Recommended Operating Conditions indicate the limits, inside which the device should be operated, to guarantee the performance given in Electrical Specifications Operating outside these limits may not necessarily cause damage to the device, but the performance may degrade outside the limits of the electrical specifications. For limits, above which damage may occur, see Absolute Maximum Ratings.

	Min	Nominal	Max	Units
T_A, Ambient Temperature	-55	+25	+100	°C
LO Input Power	+1		+15	dBm

3.4 Sequencing Requirements

There is no requirement to apply power to the ports in a specific order. However, it is recommended to provide a 50Ω termination to each port before applying power. This is a passive diode mixer that requires no DC bias.

A.4.3 Local Oscillator

ANALOG DEVICES

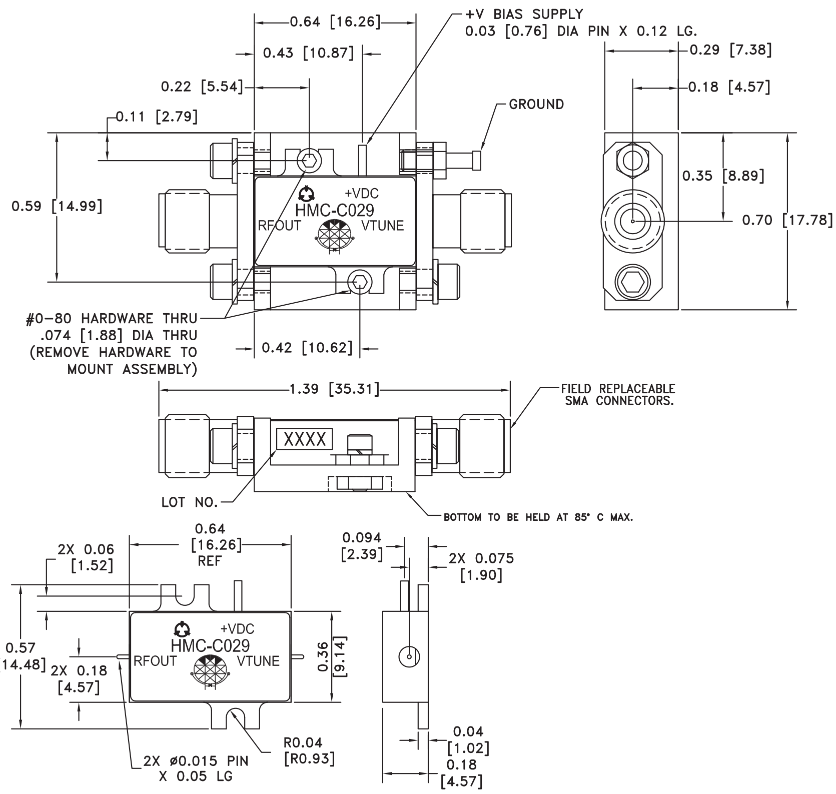
HMC-C029

v01.1007

RoHS✓ EARTH FRIENDLY

WIDEBAND VCO w/ BUFFER AMPLIFIER MODULE, 5 - 10 GHz

Outline Drawing



Package Information

Package Type	C-1
Package Weight [1]	10.2 gms [2]
Spacer Weight	N/A

[1] Includes the connectors

[2] ±1 gms Tolerance

NOTES:
1. PACKAGE, LEADS, COVER MATERIAL: KOVAR™
2. BRACKET MATERIAL: ALUMINUM.
3. PLATING: ELECTROLYTIC GOLD 50 MICROINCHES MIN., OVER ELECTROLYTIC NICKEL 75 MICROINCHES MIN.
4. ALL DIMENSIONS ARE IN INCHES [MILLIMETERS].
5. TOLERANCES: ±.010 [0.25] UNLESS OTHERWISE SPECIFIED.
6. MARK LOT NUMBER ON LABEL WHERE SHOWN, WITH .030" MIN TEXT HEIGHT.

*For price, delivery, and to place orders: Analog Devices, Inc., One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106
Phone: 781-329-4700 • Order online at www.analog.com
Application Support: Phone: 1-800-ANALOG-D*

A.4.4 Splitter

Coaxial

Power Splitter/Combiner

ZX10-2-98+
ZX10-2-98

2 Way-0° 50Ω 4750 to 9800 MHz

CASE STYLE: FL905

Connectors	Model	Price	Qty.
SMA	ZX10-2-98-S(+)	$39.95	(1-24)

+ RoHS compliant in accordance with EU Directive (2002/95/EC)

The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications.

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
Power Input (as a splitter)	1.0W max.
Internal Dissipation (as a combiner)	0.125W max.

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections

SUM PORT	3
PORT 1	1
PORT 2	2

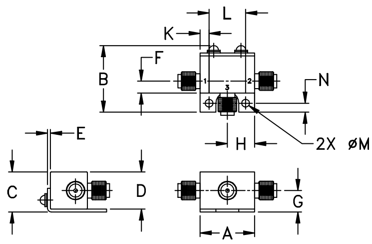
Features

- low insertion loss, 0.3 dB typ.
- excellent amplitude unbalance
- very good phase unbalance
- small size
- low cost
- protected under U.S. Patent 6,790,049 & 6,963,255

Applications

- SHF
- communications
- defense
- cable tv relay

Outline Drawing



Outline Dimensions (inch/mm)

A	B	C	D	E	F	G
.74	.90	.54	.50	.04	.16	.29
18.80	22.86	13.72	12.70	1.02	4.06	7.37

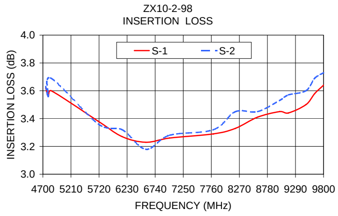
H	J	K	L	M	N	wt
.37	--	.122	.496	.106	.122	grams
9.40	--	3.10	12.60	2.69	3.10	20.0

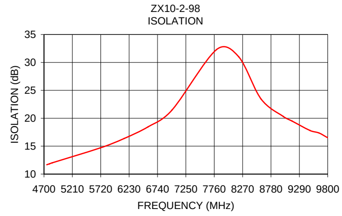
Electrical Specifications (T_{AMB}=25°C)

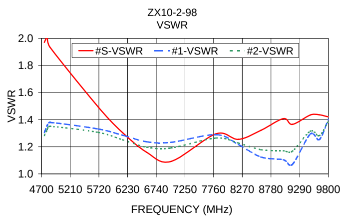
FREQ. RANGE (MHz)	ISOLATION (dB)		INSERTION LOSS (dB) ABOVE 3.0 dB		PHASE UNBALANCE (Degrees)	AMPLITUDE UNBALANCE (dB)
f_L-f_U	Typ.	Min.	Typ.	Max.	Max.	Max.
4750-9800	**23**	**10**	**0.3**	**1.2**	**9.0**	**0.5**
7000-9000	23	18	0.3	0.8	8.0	0.4

Typical Performance Data

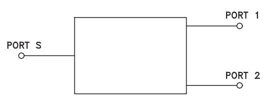
Frequency (MHz)	Insertion Loss (dB) S-1	Insertion Loss (dB) S-2	Amplitude Unbalance (dB)	Isolation (dB)	Phase Unbalance (deg.)	VSWR S	VSWR 1	VSWR 2
4750.00	3.62	3.63	0.01	11.68	0.03	1.97	1.31	1.28
4800.00	3.56	3.56	0.01	11.85	0.16	2.01	1.35	1.33
4850.00	3.60	3.69	0.09	12.02	0.20	1.93	1.38	1.35
5710.00	3.38	3.36	0.03	14.69	0.09	1.49	1.33	1.31
6140.00	3.27	3.32	0.05	16.37	0.09	1.30	1.29	1.25
6570.00	3.23	3.18	0.05	18.46	0.22	1.16	1.24	1.20
7000.00	3.26	3.28	0.02	21.45	0.22	1.09	1.23	1.19
7800.00	3.29	3.32	0.03	32.30	0.26	1.29	1.29	1.26
8200.00	3.33	3.45	0.12	31.01	0.02	1.25	1.22	1.23
8600.00	3.41	3.45	0.05	23.48	0.52	1.32	1.12	1.18
9000.00	3.45	3.53	0.08	20.33	0.98	1.41	1.10	1.17
9160.00	3.44	3.57	0.13	19.49	0.70	1.37	1.07	1.17
9480.00	3.50	3.60	0.10	17.81	0.50	1.43	1.29	1.31
9640.00	3.58	3.69	0.11	17.38	0.85	1.44	1.25	1.28
9800.00	3.64	3.73	0.09	16.51	1.35	1.42	1.40	1.39







electrical schematic



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REV. E
M98898
ZX10-2-98
ED-10280/1
HY/RS/CP
080226

A.4.5 IF LNA 1

Coaxial

Low Noise Amplifier

ZX60-33LNR-S+

50Ω 50 to 3000 MHz

Features
- wide bandwidth, 50 to 3000 MHz
- low noise figure 1.1 dB typ.
- output power, up to 19 dBm typ.
- high OIP3, up to 35 dBm, typ.
- protected by US patent 6,790,049

Applications
- front-end amplifier
- cellular
- GPS
- bluetooth
- lab
- instrumentation
- test equipment

Generic photo used for illustration purposes only

CASE STYLE: GC957

Connectors	Model
SMA	ZX60-33LNR-S+

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Electrical Specifications at 25°C

Parameter	Condition (MHz)	Min	Typ.	Max.	Units
Frequency	—	50	—	3000	MHz
Noise Figure		—	1.1	—	dB
Gain	100 1000 2000 3000	— — 13 —	24.7 18.7 14.1 11.4	— — — —	dB
Gain Flatness		—	—	—	dB
Output Power at 1dB compression		14.5	19	—	dBm
Output third order intercept point		—	+35	—	dBm
Input VSWR		—	2.0	—	:1
Output VSWR		—	1.6	—	:1
Active Directivity		—	—	—	dB
DC Supply Voltage		—	5	—	V
Supply Current		—	70	80	mA

Maximum Ratings

Parameter	Ratings
Operating Temperature	-40°C to 85°C Case
Storage Temperature	-55°C to 100°C
DC Voltage	5.5 V
Input RF Power (no damage)	+13 dBm
Power Dissipation	0.44W

Permanent damage may occur if any of these limits are exceeded.

Notes
A. Performance and quality attributes and conditions not expressly stated in this specification document are intended to be excluded and do not form a part of this specification document.
B. Electrical specifications and performance data contained in this specification document are based on Mini-Circuit's applicable established test performance criteria and measurement instructions.
C. The parts covered by this specification document are subject to Mini-Circuits standard limited warranty and terms and conditions (collectively, "Standard Terms"); Purchasers of this part are entitled to the rights and benefits contained therein. For a full statement of the Standard Terms and the exclusive rights and remedies thereunder, please visit Mini-Circuits' website at www.minicircuits.com/MCLStore/terms.jsp

A.4.6 IF limiter 1

Coaxial

Limiter

ZFLM-252-1WL-S+

50Ω Broadband 100 to 2500 MHz

CASE STYLE: H16

Connectors	Model
SMA	ZFLM-252-1WL-S+
BRACKET (OPTION "B")	

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
RF Input Power	1.5W

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections

INPUT	SMA female
OUTPUT	SMA male

Features

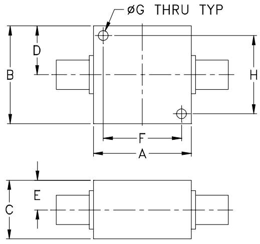
- low insertion loss, 0.7 dB typ.
- very low output power 0 dBm typ. at 30 dBm input
- low cost

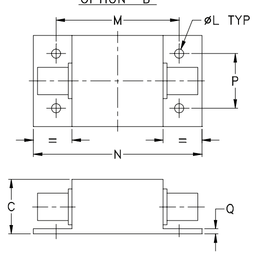
Applications

- stabilizing generator outputs
- reducing amplitude variations
- protects low noise amplifiers and other devices from ESD or input power damage

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Outline Drawing





Outline Dimensions (inch / mm)

A	B	C	D	E	F	G	H
1.25	1.25	.75	.63	.38	1.000	.125	1.000
31.75	31.75	19.05	16.00	9.65	25.40	3.18	25.40

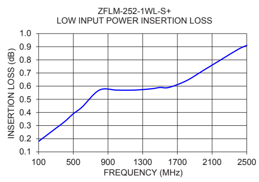
J	K	L	M	N	P	Q	wt
--	--	.125	1.688	2.18	.750	.06	grams
--	--	3.18	42.88	55.37	19.05	1.52	70.0

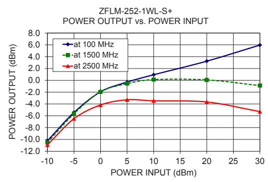
Electrical Specifications

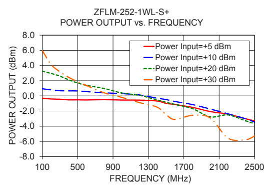
Parameter	Condition	Min.	Typ.	Max.	Units
Frequency Range		100	—	2500	MHz
Linear Range					
Max Input Power	<0.1 dB compression	—	—	-10	dBm
Insertion Loss	<-10 dBm	—	0.7	1.4	dB
VSWR	<-10 dBm	—	1.35	1.6	:1
Limiting Range					
Input Power	>1dB compression filtered signal frequency	+5	—	+30	dBm
Output Power		—	0	—	dBm
Δ Output/1dB Δ Input	Input Power Range (dBm)				dB/dB
	5 to 10	—	0.1	—	
	10 to 20	—	0.05	—	
	20 to 30	—	0.1	—	
Recovery Time	1 watt pulse 50 µsec pw 1kHz duty cycle recovery to within 90% of final value	—	8	—	nsec
Response Time	-30 to +30 dBm input 50 µsec PW 1 kHz duty cycle	—	2	—	nsec

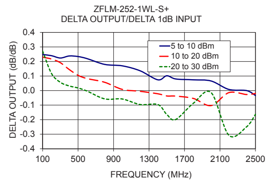
Typical Performance Data

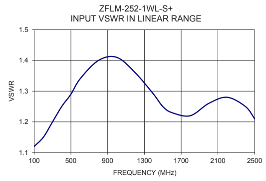
Freq. (MHz)	I. Loss in Linear Range (dB)	VSWR in Linear Range (:1)	Power Output (dBm)				Δ Output / 1dB Δ Input		
			+5 dBm Input	+10 dBm Input	+20 dBm Input	+30 dBm Input	+5 to +10 dBm Input	+10 to +20 dBm Input	+20 to +30 dBm Input
100.00	0.18	1.12	-0.30	0.94	3.24	5.96	0.25	0.23	0.27
200.00	0.23	1.15	-0.41	0.79	2.96	4.14	0.24	0.22	0.12
300.00	0.28	1.20	-0.44	0.68	2.60	3.17	0.22	0.19	0.06
400.00	0.33	1.25	-0.53	0.66	2.11	2.43	0.24	0.15	0.03
500.00	0.39	1.29	-0.52	0.65	1.70	1.88	0.23	0.11	0.02
600.00	0.44	1.34	-0.54	0.56	1.39	1.36	0.22	0.08	0.00
800.00	0.57	1.40	-0.50	0.40	0.97	0.40	0.18	0.06	-0.06
1000.00	0.57	1.41	-0.55	0.30	0.38	-0.20	0.17	0.01	-0.06
1200.00	0.57	1.36	-0.56	0.12	0.07	-0.89	0.14	-0.01	-0.10
1400.00	0.58	1.29	-0.68	-0.31	-0.53	-1.49	0.07	-0.02	-0.10
1500.00	0.59	1.25	-0.99	-0.48	-0.85	-2.49	0.10	-0.04	-0.16
1600.00	0.59	1.23	-1.14	-0.74	-1.12	-3.11	0.08	-0.04	-0.20
1800.00	0.64	1.22	-1.52	-1.15	-1.69	-2.56	0.07	-0.05	-0.09
2000.00	0.72	1.26	-2.07	-1.74	-2.77	-2.91	0.07	-0.10	-0.01
2200.00	0.80	1.28	-2.41	-2.37	-2.51	-5.58	0.01	-0.01	-0.31
2400.00	0.88	1.25	-3.02	-3.02	-3.29	-5.78	0.00	-0.03	-0.25
2500.00	0.91	1.21	-3.29	-3.46	-3.66	-5.29	-0.03	-0.02	-0.16

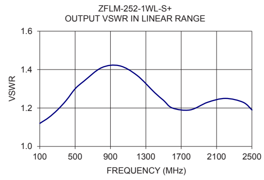












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REV. B
M171494
ZFLM-252-1WL-S+
ED-14683
DJ/CP/AM
190110

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A.4.7 IF LNA 2

Coaxial

Low Noise Amplifier

ZX60-P105LN+

50Ω 40 to 2600 MHz

Features
- excellent gain flatness, ±0.25 dB over 0.1 - 2.0 GHz
- low noise figure, 1.9 dB typ. at 2 GHz
- gain, 15 dB typ. at 2 GHz
- high IP3, 39 dBm typ. at 0.9 GHz
- unconditionally stable
- protected by US patent 6,790,049

Applications
- base station infrastructure
- portable wireless
- catv & DBS
- MMDS & wireless LAN
- LTE

Generic photo used for illustration purposes only

CASE STYLE: GC957

Connectors	Model
SMA	ZX60-P105LN+

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Electrical Specifications at 25°C

Parameter	Condition (MHz)	Min.	Typ.	Max.	Units
Frequency Range		40		2600	MHz
Noise Figure	40		2.3		dB
	500		2.0		
	900		1.9		
	2000		1.9	2.7	
	2600		2.0		
Gain	40		14.4		dB
	500		14.5		
	900		14.4		
	2000	13.8	15.5	16.8	
	2600		15.1		
Gain Flatness	1000 - 2000		±0.25		dB
Output Power @ 1 dB compression	40		19.5		dBm
	500		21.0		
	900		21.0		
	2000		18.9		
	2600		19.4		
Output IP3	40		34.6		dBm
	500		38.7		
	900		37.4		
	2000		33.6		
	2600		33.2		
Input VSWR	40		2.2		dB
	500		1.2		
	900		1.2		
	2000		1.3		
	2600		1.8		
Output VSWR	40		1.1		dB
	500		1.2		
	900		1.1		
	2000		2.4		
	2600		2.2		
Active Directivity (Isolation-Gain)	40		6.3		dB
	500		4.5		
	900		5.1		
	2000		8.1		
	2600		13.5		
DC Supply Voltage		4.8	5.0	5.2	V
Supply Current		—	63	77	mA

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A.4.8 IF filter

Coaxial

Bandpass Filter

VBF-1445+

50Ω 1420 to 1470 MHz

CASE STYLE: FF704

Connectors	Model
SMA	VBF-1445+

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-55°C to 100°C
Storage Temperature	-55°C to 100°C
RF Power Input*	1.5W max. at 25°C

*Passband rating, derate linearly to 0.25W at 100°C ambient
Permanent damage may occur if any of these limits are exceeded.

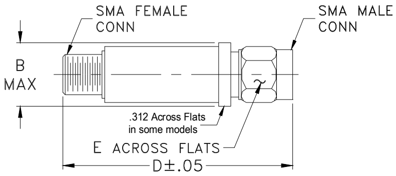
Features

- Small size
- Temperature stable
- Rugged unibody construction

Applications

- Harmonic Rejection
- Transmitters / Receivers

Outline Drawing



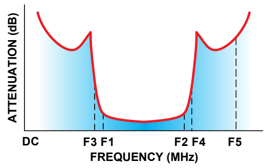
Outline Dimensions (inch / mm)

B	D	E	
.410	1.43	.312	gra
10.41	36.32	7.92	1

Electrical Specifications at 25°C

Parameter		F#	Frequency (MHz)	Min.	Typ.	Max.	Unit
Pass Band	Center Frequency	—	—	—	1445	—	MHz
	Insertion Loss	F1-F2	1420-1470	—	—	3.0	dB
	VSWR	F1-F2	1420-1470	—	—	2.5	:1
Stop Band, Lower	Insertion Loss	DC-F3	DC-1140	—	20	—	dB
	VSWR	DC-F3	DC-1140	—	25	—	:1
Stop Band, Upper	Insertion Loss	F4-F5	2600-4900	—	25	—	dB
	VSWR	F4-F5	2600-4900	—	20	—	:1

Typical Frequency Response



Functional Schematic

Typical Performance Data at 25°C

Frequency (MHz)	Insertion Loss (dB)	VSWR (:1)
0.30	65.58	1781.84
300.00	37.88	99.19
700.00	38.27	70.89
1000.00	42.94	49.30
1075.00	39.44	40.47
1180.00	21.37	23.31
1300.00	6.24	3.89
1420.00	2.23	1.65
1470.00	2.03	1.31
2050.00	19.89	47.56
2400.00	26.38	60.68
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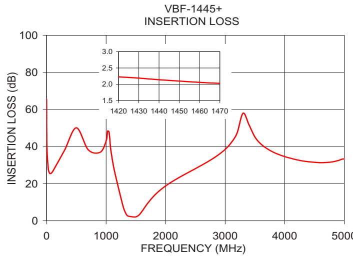
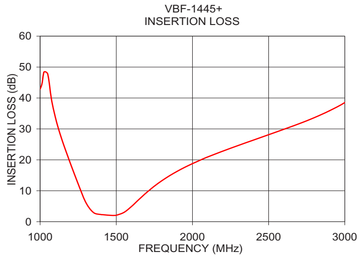
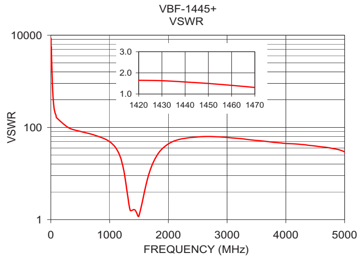
2800.00	33.65	62.92
3800.00	37.12	47.50
4900.00	32.50	32.93







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VBF-1445+
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151020

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A.4.9 IF limiter 2

Coaxial

Limiter

ZFLM-252-1WL-S+

50Ω Broadband 100 to 2500 MHz

CASE STYLE: H16

Connectors	Model
SMA	ZFLM-252-1WL-S+
BRACKET (OPTION “B”)	

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Maximum Ratings

Operating Temperature	-40°C to 85°C
Storage Temperature	-55°C to 100°C
RF Input Power	1.5W

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections

INPUT	SMA female
OUTPUT	SMA male

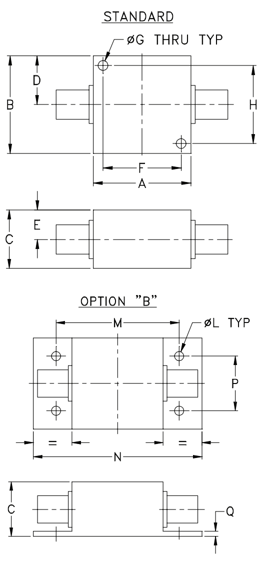
Features

- low insertion loss, 0.7 dB typ.
- very low output power 0 dBm typ. at 30 dBm input
- low cost

Applications

- stabilizing generator outputs
- reducing amplitude variations
- protects low noise amplifiers and other devices from ESD or input power damage

Outline Drawing



Outline Dimensions (inch / mm)

A	B	C	D	E	F	G	H
1.25	1.25	.75	.63	.38	1.000	.125	1.000
31.75	31.75	19.05	16.00	9.65	25.40	3.18	25.40

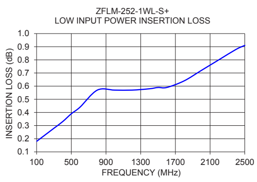
J	K	L	M	N	P	Q	wt
--	--	.125	1.688	2.18	.750	.06	grams
--	--	3.18	42.88	55.37	19.05	1.52	70.0

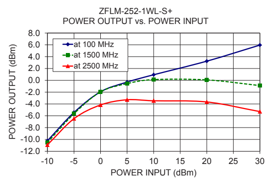
Electrical Specifications

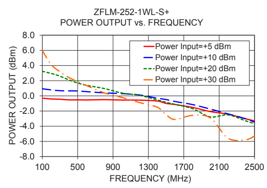
Parameter	Condition	Min.	Typ.	Max.	Units
Frequency Range		100	—	2500	MHz
Linear Range					
Max Input Power	<0.1 dB compression	—	—	-10	dBm
Insertion Loss	<-10 dBm	—	0.7	1.4	dB
VSWR	<-10 dBm	—	1.35	1.6	:1
Limiting Range					
Input Power	>1dB compression filtered signal frequency	+5	—	+30	dBm
Output Power		—	0	—	dBm
Δ Output/1dB Δ Input	Input Power Range (dBm)				dB/dB
	5 to 10	—	0.1	—	
	10 to 20	—	0.05	—	
	20 to 30	—	0.1	—	
Recovery Time	1 watt pulse 50 µsec pw 1kHz duty cycle recovery to within 90% of final value	—	8	—	nsec
Response Time	-30 to +30 dBm input 50 µsec PW 1 kHz duty cycle	—	2	—	nsec

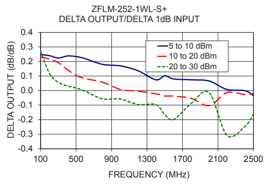
Typical Performance Data

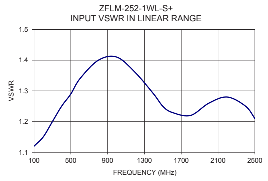
Freq. (MHz)	I. Loss in Linear Range (dB)	VSWR in Linear Range (:1)	Power Output (dBm)				Δ Output / 1dB Δ Input		
			+5 dBm Input	+10 dBm Input	+20 dBm Input	+30 dBm Input	+5 to +10 dBm Input	+10 to +20 dBm Input	+20 to +30 dBm Input
100.00	0.18	1.12	-0.30	0.94	3.24	5.96	0.25	0.23	0.27
200.00	0.23	1.15	-0.41	0.79	2.96	4.14	0.24	0.22	0.12
300.00	0.28	1.20	-0.44	0.68	2.60	3.17	0.22	0.19	0.06
400.00	0.33	1.25	-0.53	0.66	2.11	2.43	0.24	0.15	0.03
500.00	0.39	1.29	-0.52	0.65	1.70	1.88	0.23	0.11	0.02
600.00	0.44	1.34	-0.54	0.56	1.39	1.36	0.22	0.08	0.00
800.00	0.57	1.40	-0.50	0.40	0.97	0.40	0.18	0.06	-0.06
1000.00	0.57	1.41	-0.55	0.30	0.38	-0.20	0.17	0.01	-0.06
1200.00	0.57	1.36	-0.56	0.12	0.07	-0.89	0.14	-0.01	-0.10
1400.00	0.58	1.29	-0.68	-0.31	-0.53	-1.49	0.07	-0.02	-0.10
1500.00	0.59	1.25	-0.99	-0.48	-0.85	-2.49	0.10	-0.04	-0.16
1600.00	0.59	1.23	-1.14	-0.74	-1.12	-3.11	0.08	-0.04	-0.20
1800.00	0.64	1.22	-1.52	-1.15	-1.69	-2.56	0.07	-0.05	-0.09
2000.00	0.72	1.26	-2.07	-1.74	-2.77	-2.91	0.07	-0.10	-0.01
2200.00	0.80	1.28	-2.41	-2.37	-2.51	-5.58	0.01	-0.01	-0.31
2400.00	0.88	1.25	-3.02	-3.02	-3.29	-5.78	0.00	-0.03	-0.25
2500.00	0.91	1.21	-3.29	-3.46	-3.66	-5.29	-0.03	-0.02	-0.16

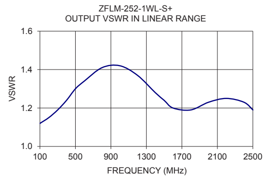












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REV. B
M171494
ZFLM-252-1WL-S+
ED-14683
DJ/CP/AM
190110

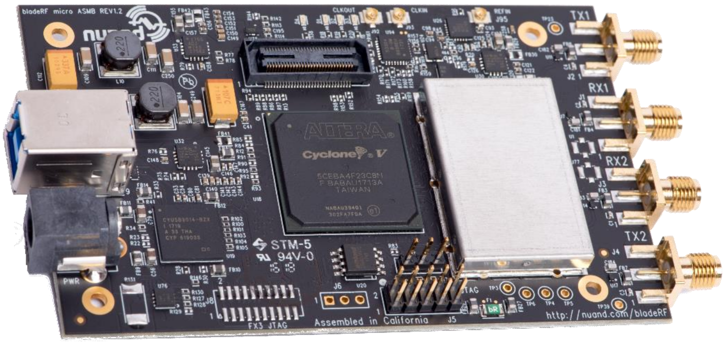
A.4.10 SDR

bladeRF 2.0

USB 3.0 Software Defined Radio

The bladeRF is an off-the-shelf USB 3.0 Software Defined Radio (SDR) that is easy and affordable for students and RF enthusiasts to explore wireless communications, yet provides a powerful waveform development platform expected by industry professionals.

Support is available for Linux, macOS, and Windows. The bladeRF libraries, utilities, firmware, and platform HDL are released under open source licenses, and schematics are available online. The FPGA and USB 3.0 peripheral controller are programmable using vendor-supplied tools and SDKs that are available online, free of charge.



FEATURES

Analog Devices RF Transceiver
- 47 MHz to 6 GHz frequency range
- 2x2 MIMO, 61.44 MHz sampling rate
- 56 MHz filtered bandwidth (IBW)
- Automatic gain control (AGC)
- Real-time custom gain control tables controlled via SPI and discrete external input pins
- Automatic IQ and DC offset correction
- 128-tap digital FIR filtering

USB 3.0 SuperSpeed Support
- Cypress FX3 peripheral controller with integrated 200 MHz ARM926EJ-S processor
- Fully bus-powered over USB 3.0
- External power option via 5 V DC barrel jack with automatic switchover

Altera Cyclone V FPGA
- 49 kLE and 301 kLE variants available for custom signal processing and hardware accelerators

Factory-calibrated SiTime MEMS VCTCXO
- Calibrated within 1 Hz of 38.4 MHz
- Taming supported via 12-bit DAC or ADF4002 PLL
- MEMS oscillators provide superior reliability, aging, power supply noise rejection, and vibe/shock performance compared to quartz oscillators

Fully Customizable
- Expansion port with 32 I/O pins (LVDS available)
- JTAG connectors
- Triggered multi-device sampling synchronization
- Onboard bias tee optionally provides 5 V to active antennas and accessories

SOFTWARE SUPPORT & APPLICATIONS

Supported by popular third-party software[1]
- GNU Radio via gr-osmosdr
- Pothos via SoapySDR
- SDRangel
- SDR Console
- SDR# via sdrsharp-bladeRF
- YateBTS
- OpenAirInterface
- srsUE & srsLTE
- MathWorks MATLAB® & Simulink® support
- Python bindings

Applications
- Custom modem and waveform development
- Wireless video (e.g., ATSC, DVB-T, DVB-S)
- GPS reception and simulation
- Whitespace exploration
- GSM and LTE
- ADS-B reception and simulation

Operating Systems
- Linux
- Windows
- macOS

[1] *Third-party software is copyrighted by the respective owners and/or contributors.*

bladeRF@nuand.com
https://www.nuand.com

720 East Ave Suite 201
Rochester, NY 14607

A.4.11 ADC

ANALOG DEVICES

RF Agile Transceiver

Data Sheet **AD9361**

FEATURES

RF 2 × 2 transceiver with integrated 12-bit DACs and ADCs
TX band: 47 MHz to 6.0 GHz
RX band: 70 MHz to 6.0 GHz
Supports TDD and FDD operation
Tunable channel bandwidth: <200 kHz to 56 MHz
Dual receivers: 6 differential or 12 single-ended inputs
Superior receiver sensitivity with a noise figure of 2 dB at 800 MHz LO
RX gain control
- **Real-time monitor and control signals for manual gain**
- **Independent automatic gain control**

Dual transmitters: 4 differential outputs
Highly linear broadband transmitter
- **TX EVM: ≤−40 dB**
- **TX noise: ≤−157 dBm/Hz noise floor**
- **TX monitor: ≥66 dB dynamic range with 1 dB accuracy**

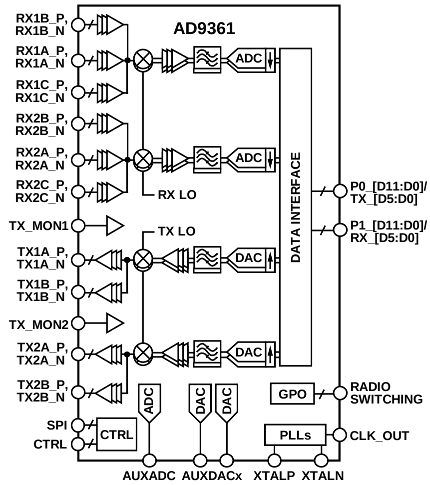
Integrated fractional-N synthesizers
- **2.4 Hz maximum local oscillator (LO) step size**

Multichip synchronization
CMOS/LVDS digital interface

APPLICATIONS

Point to point communication systems
Femtocell/picocell/microcell base stations
General-purpose radio systems

FUNCTIONAL BLOCK DIAGRAM



NOTES
1. SPI, CTRL, P0_[D11:D0]/TX_[D5:D0], P1_[D11:D0]/RX_[D5:D0], AND RADIO SWITCHING CONTAIN MULTIPLE PINS.

10453-001

Figure 1.

GENERAL DESCRIPTION

The AD9361 is a high performance, highly integrated radio frequency (RF) Agile Transceiver™ designed for use in 3G and 4G base station applications. Its programmability and wideband capability make it ideal for a broad range of transceiver applications. The device combines a RF front end with a flexible mixed-signal baseband section and integrated frequency synthesizers, simplifying design-in by providing a configurable digital interface to a processor. The AD9361 receiver LO operates from 70 MHz to 6.0 GHz and the transmitter LO operates from 47 MHz to 6.0 GHz range, covering most licensed and unlicensed bands. Channel bandwidths from less than 200 kHz to 56 MHz are supported.

The two independent direct conversion receivers have state-of-the-art noise figure and linearity. Each receive (RX) subsystem includes independent automatic gain control (AGC), dc offset correction, quadrature correction, and digital filtering, thereby eliminating the need for these functions in the digital baseband. The AD9361 also has flexible manual gain modes that can be externally controlled. Two high dynamic range analog-to-digital converters (ADCs) per channel digitize the received I and Q signals and pass them through configurable decimation filters and 128-tap finite impulse response (FIR) filters to produce a 12-bit output signal at the appropriate sample rate.

The transmitters use a direct conversion architecture that achieves high modulation accuracy with ultralow noise. This transmitter design produces a best in class TX error vector magnitude (EVM) of <−40 dB, allowing significant system margin for the external power amplifier (PA) selection. The on-board transmit (TX) power monitor can be used as a power detector, enabling highly accurate TX power measurements.

The fully integrated phase-locked loops (PLLs) provide low power fractional-N frequency synthesis for all receive and transmit channels. Channel isolation, demanded by frequency division duplex (FDD) systems, is integrated into the design. All VCO and loop filter components are integrated.

The core of the AD9361 can be powered directly from a 1.3 V regulator. The IC is controlled via a standard 4-wire serial port and four real-time input/output control pins. Comprehensive power-down modes are included to minimize power consumption during normal use. The AD9361 is packaged in a 10 mm × 10 mm, 144-ball chip scale package ball grid array (CSP_BGA).

Rev. F **Document Feedback**

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700
Technical Support **www.analog.com**

Appendix B

Code

B.1 Code for Plots

```
close all;
clear;

% Physical constants
c = physconst('Lightspeed');     % Speed of light
k = physconst('Boltzmann');      % Boltzmann's constant
T0 = 290;                        % Temperature [K]

% Transmitter chain
Pt = 3;                          % Transmitted power [W]
% Pt = Pt*10^6;
Gt = 24.7; Gt = db2pow(Gt);      % Transmitter antenna gain [dB->ratio]
Lt = 0; Lt = db2pow(Lt);         % Transmitter loss [dB->ratio]

% Receiver chain
Gr = 8; Gr = db2pow(Gr);       % Receiver antenna gain [dB->ratio]
GrMin = 3; GrMin = db2pow(GrMin); % Receiver antenna gain minimum [ddB->ratioB]
Lr = 3; Lr = db2pow(Lr);         % Receiver loss [dB->ratio]

% General
B = 50e6;                        % Band-pass Bandwith [Hz]
f = 9.7*10^9;                    % Frequency [Hz]
lambda = c/f;                    % Wave length [m]
SNRmin = 10;                     % Sigal-to-noise ratio [dB]
Gp = 10;                         % Processing gain [dB]
% Gp = 32;                          % Processing gain [dB]

% Noise power
NF = 3.2; F = db2pow(NF);           % Noise figure [dB->ratio]
Pn = (k*B*T0); Pn = pow2db(Pn); % Noise power [dB]
Pn = Pn + 30;                    % [dBm]

% Target reflection
sigma = 1;                       % general RCS [m^2]
sigmaMax = 10;                   % maximum RCS [m^2]

% Miscellanious variables
Rr = 300;                        % Receiver to target distance [m]
Rr = 100;                        % Alternate plot
L = 0; L = db2pow(L);            % Extra loss [dB->ratio] (for safety margins)
```

```
% Noise floor and minimum required SNR
% noiseFloor = -174+NF+pow2db(B); % Noise floor [dBm]
noiseFloor = Pn+NF;                % Noise floor [dBm]
reqSNR = noiseFloor-Gp+SNRmin;     % Required SNR for quantisation [dB]

% Defining variables for loop
n = 500;                           % Amount of measuring points
mult = 10;                         % Increase in distance per measuring point
% Define matrices
Pmin = zeros(1,3);                 % Minimum power
Pmax = zeros(1,3);                 % Maximum power
Pindirect = zeros(1,n);            % Power of indirect path
Pdirect = zeros(1,n);              % Power of direct path
lines = zeros(2,n);                % Define comparison lines for plot
R = zeros(1,2);                    % Define range matrice

for i=1:n
    % Define distance between transmitter and receiver, Rr is constant
    Rt=i*mult;
    % Calculate indirect path
    Pindirect(i)=receivedpower(Rt,Rr,Pt,pow2db(GrMin),pow2db(Lr),NF,sigma,L,1);
    % Calculate direct path
    Rd=Rt;                         % Direct path [m]
    FSPL=(4*pi*Rd*f/c)^2;
    Pdirect(i)=pow2db(Pt*(Gt*Gr*1/L)/FSPL)+30;
    % Calculate comparison lines
    lines(1,i)=noiseFloor;
    lines(2,i)=reqSNR;
end
R(1) = 304.8;                                   % Define minimum range
R(2) = 2.5e3;                                   % Define maximum range
Pmax(1) = Pdirect(uint8(R(1)/mult));            % Get maximum power from calc
Pmax(2) = Pdirect(uint8(R(1)/2/mult));          % Maximum power to determine limiters
% Pmax(3) = Pdirect(uint8(10/mult));              % Maximum power due to accident
Pmax(3) = pow2db(Pt*(Gt*Gr*1/L)/((4*pi*1*f/c)^2))+30;       % Maximum power due to accident
Pmin(1) = reqSNR;                               % Define min power from max possible value
Pmin(2) = Pindirect(uint8(R(2)/mult));          % Get minimum power
D = Pmax(1)-Pmin(1);                            % Dynamic range [dB]

% Calculate the required gain
Dsdr = mag2db(2^12);                    % Calculate dynamic range of the SDR
Doffset=Dsdr-D;                         % + is good, - means variable attenuator req
Psdr = 2.5;                             % Define max SDR power [dBm]
Psdrm = Psdr-Dsdr;                      % Calculate min SDR power [dBm]
Greq = Psdrm-Pmin(1);                   % Calculate required gain [dB]
Lchain = 1+2+9.5+0.6+2+0.6;             % Chain losses [dB]
% LimiterRF+FilterRF+Mixer+LimiterIF1+FilterIF+LimiterIF2
Gtotal = Greq + Lchain;                 % Total gain from req gain and chain losses [dB]

% Calculate RtRr product
RtRr2 = (Pt*Gt*Gr*db2pow(Gp)*sigma*((lambda)^2))/(((4*pi)^3)*Lr*Lt*L*db2pow(Pn-30));
disp(nthroot(RtRr2,4))
% Define plot variables
r = mult:mult:mult*n;              % Define the axis to plot against
plots = zeros(1,mult);
label = strings(1,mult);
colors = hsv(mult);

% --- PLOTS ---
% Plot the different calculated powers against the distance
```

```
figure(1)
hold on
plot(r,Pindirect)
plot(r,Pdirect)
plot(r,lines)
%plot(r,lines(1,:))

y = get(gca,'YLim');
x=[uint8(R(1)) uint8(R(1))];
line(x, y,'Color','r');
x=[uint16(R(2)) uint16(R(2))];
line(x, y,'Color','r');

title("Power received with "+Rr+"m distance between receiver and target")
temp1=sprintf('Min range: %d', uint16(R(1))); temp2=sprintf('Max range: %d', uint16(R(2)
    ));
legend('Reflect','Direct path','Noise floor','Minimum required SNR',temp1,temp2)
%legend('Reflect','Direct path','Noise floor',temp1,temp2)
delete temp1; delete temp2;
ylabel('Power [dBm]')
xlabel('Distance between receiver and transmitter [m]')

% Pr=receivedpower(152.8,152.8,Pt,pow2db(Gr),pow2db(Lr),NF,sigma,L,0);
```

B.2 Code to Calculate Receiver Power

```
function Pr = receivedpower(Rt, Rr, Pt, Gr, Lr, NF, sigma, L, toggle)
%RECEIVEDPOWER calculates the received power in dBm.
%   Pr = receivedpower(Rt, Rr, )
%   - Rt = distance betweeen transmitter and target (in meters)
%   - Rr = distance betweeen receiver and target (in meters)
%   - toggle = toggle for casini plots

% Physical constants
c = physconst('Lightspeed');     % Speed of light
k = physconst('Boltzmann');      % Boltzmann's constant
T0 = 290;                        % Temperature [K]

% Transmitter chain
% Pt = 3;                          % Peak transmit power  [W]
Gt = 24.7; Gt = db2pow(Gt);      % Transmitter antenna gain [dB->ratio]
Lt = 0; Lt = db2pow(Lt);         % Transmitter loss [dB->ratio]

% Receiver chain
Gr = db2pow(Gr);                 % Receiver gain [dB]
Lr = db2pow(Lr);                 % Receiver losses in system [dB]
F = db2pow(NF);                  % Noise figure at receiver [dB]

% General
B = 15e6;                        % Bandwidth [Hz]
Bn = 50e6;                       % Band-pass Bandwith [Hz]
f = 9.7*10^9;                    % Frequency [Hz]
lambda = c/f;                    % Wave length [m]
% SNRmin= -10;                     % Sigal-to-noise ratio [dB]

% Noise power
N = k*T0*F*Bn;                   % Noise power [W]

% Waveform Parameters
tau = 200e-6;                    % Pulse duration
Gp = B*tau;                      % Processing gain
```

```
Gp = 10;                          % Matched filter gain
Gp = db2pow(Gp);                  % dB -> ratio

% Constant for radar range equation
K = (Pt*Gt*Gr*Gp*sigma*((lambda)^2))/(((4*pi)^3)*Lr*Lt*L*N);
% Signal to noise ratio / Receiver power [dBm]
SNRmin = K/((Rt^2)*(Rr^2)); SNRmin = pow2db(SNRmin);
Pr = SNRmin + pow2db(N) + 30;

% Toggles: 0 is plot, 1 returns Pr, 2 returns K (constant), 3 returns SNRmin
if(toggle==1)
    Pr = Pr;
elseif(toggle==2)
    Pr = K;
elseif(toggle==3)
    Pr = SNRmin;
elseif(toggle==0)
     L = Rt;                               % Distance between transmitter and receiver
     SNR = linspace(SNRmin,SNRmin+6*3,7);     % Signal-to-Noise Ratio\
     plots = zeros(1,2*length(SNR));
     label = strings(1,length(SNR));
     colors = hsv(length(SNR));

    figure
    for i = 1:length(SNR)
        SNR_i = db2pow(SNR(i));
        a = L/2;
        b = (K/SNR_i)^(1/4);
        [x,y] = cassini(a,b,0);
        x = real(x); y = real(y);

        label(i) = sprintf('SNR = %.1f dB', pow2db(SNR_i));
        hold on
        plots(i) = plot((x(1,:)+L/2)*1e-3,(y(1,:)*1e-3), 'color', colors(i,:));
        % plots(i) = plot((x(1,:)+L/2)*1e-3,(y(1,:)*1e-3), 'color', colors(i,:));

        % When multiple ovals have the same SNR assign the same color
%           if a > b
%               plots(i+1) = plot((x(2,:)+L/2)*1e-3,(y(2,:)*1e-3),...
%                   'color', colors(i,:));
%           end
    end
    legend(plots(1:i),label(1:i),'location','south');
    % disp(plotss)
    plot(0,0,'x','DisplayName','Tx')
    plot(L/1e3,0,'x','DisplayName','Rx')
    hold off
    xlabel('Range (km)')
    ylabel('Range (km)')
    title(['Ovals of Cassini with SNR_{min} = ',num2str(SNRmin),' dB'])
    axis equal
    grid
    box on
    set(gcf,'PaperPositionMode','auto');
end
end
```

B.3 Code for DoA Algorithm

```
clear all
close all
```

```
%% input variables
SNR = -10;
theta = [0];
runs = 1000;
sensitivity = 20;
%% Code
c=physconst('lightspeed');
T=1e-3;
B=2e7;
fc=1.5e9;
fs= 2e7;
N = 2;
R=5000;
t=0:1/fs:(T-1/fs);
n = 0:N-1;
k=B/T;
lambda=c/fc;
d = 1*(lambda/2);
tau=R/c;
angle_diff=0;
angle=0;

SNR = db2mag(2*SNR);
    signal= (SNR/(SNR+1)); %the normalised SNR
    noise = (1/(SNR+1));
succesfull_scan =0;
%% Setting figure
if runs> 1
    axis([0 runs -90 90]);
    xlabel('Total Runs');
    ylabel('Angle [degrees]');
    hold on
end
%% Start of loop
for j= 1:runs
%% Possible theta variations
    theta(j) = 60*sind(j*360/runs);
%     theta = (theta2(2)-theta2(1))/2*sind(j*360/runs) + (theta2(2)+theta2(1))/2;

%% Simulation Part of the code
    %%Signal
    a=exp(2i.*pi.*n*d.*sind(theta(j))./lambda).'; % Make the steering vector
    r=exp(1i*pi*k.*(t-tau).^2 - 2i*pi*fc*tau); % Make the incoming signal
    rm = a*r; %Add the signals togehter
    %%Noise addition
        for i=1:(N)
            rm(i,:) =signal*rm(i,:) + (noise*(wgn(length(t),1,1))+1i*(wgn(length(t),1,1))).';
        end
%%

%%  AoA calculation part
    %%The matched filter
    x=exp(1i*pi*k.*t.^2);
    h=conj(x(end:-1:1)); %create the conjugate time inversed signal for the matched filter
    for i=1:N
        dm(i,:)=conv(rm(i,:),h,'same'); %apply the matched filter.
    end
    %% The Fast Fourier over the one time width antenna values
    degrees = asind(linspace(-1,1,2^10)); %redefining the x-axis as sin(theta) isntead
```

```
    of theta
    test = fftshift(fft(dm,2^10,1),1);  %the actual FFT
    max1 = max(test.'); %angle extracted out of the fftshift
    [max2,i] = max(max1);
    max3(j)=db(max2);
    %%
    if max3(j) > sensitivity %checks if there is a signal or just noise
        if(j > 1) %checks if this is not the first run, because of angle_diff
            if isnan(angle(j-1)) == 1;  %checks if last value has a NaN, or no signal
                angle(j)= degrees(i);   %If so no negative feedback is applied.
                angle_diff(j)=0;
            else
                if abs(degrees(i) - angle(j-1)) < 35    %checks if the value falls in line with reasonable new values.
                    angle_diff(j) = (angle(j-1) - degrees(i));
                    angle(j) = angle(j-1) - 0.5*angle_diff(j); %the new value with feedback
                else
                    angle(j) = angle(j-1);                      %if value falls out of bounds it keeps the same value.
                    angle_diff(j) = (angle(j-1)-degrees(i));
                end
            end

        else
            angle(j) = degrees(i);  %first value
        end
        %%
        if angle(j) > 0
            up_down(j) = 1; %calculates if the object is above or below the drone
        elseif angle(j) < 0
            up_down(j) = -1;
        end
        if runs > 1 %plot if more than one run
            plot(angle,'b');
            hold on
            plot(theta+4,'k')
            hold on
            plot(theta-4,'k')
            %plot(up_down,'b');
            hold on
            angle_mean(j) = mean(angle);
            drawnow;
        end
        % end
            if ((angle(j) >= theta(j) - 4) && (angle(j) <= theta(j) + 4)) %adds a number to succesful scan if its in the boundaries
                succesfull_scan(j)= 1;
            end
    else %Sets a value to NaN if no signal is detected
        angle(j)=NaN;
    end

end
succesfull_percentage = sum(succesfull_scan)/runs;
```

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