Broadband, Rugged, High Linearity, Low-Noise Amplifier

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Abstract
This report examines the application of a low-noise amplifier module for a Global Positioning System (GPS). This low-noise amplifier module helps allow the carrier signal to get the amplification needed to give a smoother analog to digital conversion. However, the frequency range of the GPS spectrum reaches up to 1.6GHz, where component noise becomes an issue and can create a disrupted signal. This low-noise amplifier needs to create a reasonable gain, while achieving a low noise figure. An amplifier with high gain and low noise figure becomes difficult because they create a design trade-off, higher the gain brings higher the noise figure. This report shows the trade-offs of gain and noise figure and a way of designing a reasonable amplifier for higher frequencies.
1.0 Introduction

The GLONASS Global Positioning System (GPS) has become a huge development in the last several years. The GPS integrates into many devices as a secondary function, including cell phones, cars, and airplanes. They also have their own product line on the market. More specifically the GLONASS GPS has grown high interest in the GPS market competing against the dominating U.S. market [1]. Popular devices designed in the U.S. have included the Russian GLONASS systems and satellites; for example, the iPhone 4S and iPhone 5 have integrated the system into their cellular devices and even their tablets the iPad [2][3][4]. As the GLONASS system becomes more desirable, the design needs new upgrades to the design. This report examines the low-noise module used in the receiver of a GLONASS system.

The low-noise amplifier allows an essential piece to the GLONASS system. In any GPS system, the device receives a small signal from a satellite through space. The signal usually comes at low power and needs amplification for an accurate position reading. Many analog-to-digital converters require a range of input power for any conversion; therefore, amplifying the signal significantly becomes important. However, amplifying a RF signal becomes difficult at higher frequencies, and design trade-offs become relevant. At higher frequencies, components show higher levels of noise, such as thermal noise, shot noise, and flicker noise. This concerns the possible gain because designing for a lower noise figure affects the amount of possible gain allowed by the amplifier. This report depicts the trade-offs in a low-noise amplifier as it designs one for the specifications of a low-noise amplifier in the GLONASS system.
2.0 Background

The specifications for this project come from the International Microwave Symposium (IMS) student competition; which is held every year sponsoring a low-noise amplifier competition. The rules below show the requirements for all contestants:

- Competitors are required to design, construct, measure, and demonstrate a broadband high linearity, low-noise amplifier module at 1.1 GHz- 1.6 GHz, the civil part of the GPS frequency and the parallel Russian GLONASS system.

- The amplifier may use any technology. Use of commercial amplifier subsystems and passive components is allowed.

- The amplifier shall allow for internal inspection of the circuitry.

- The amplifier shall be capable of amplifying a 1.1 GHz-1.6 GHz signal with a minimum 13-dB of small-signal gain over the band with a 50-ohm source and load impedance.

- The noise figure must be lower than 1.5 dB at both 1.1GHz and 1.6GHz

- The P1dB (1dB compressed, single tone) output power should be greater than 3 dBm for both 1.1 and 1.6GHz.- The amplifier must have no DC voltage at its input and output ports.

- The amplifier must be operated at room temperature.

- The amplifier must utilize 3.5 mm SMA (female at the input, male at the output) connectors on both the input and output. The prime power shall use two wires with banana plugs at least 0.5 meter in length and it must be shielded. The hot connector must be in red with ground in black. The device must be ruggedized and shielded to work in a noisy environment. This is a central requirement as in the past unshielded devices could not be measured in the noisy environment of an exhibition hall at IMS due to electromagnetic interference (EMI). The LNA module enclosure should be shielded completely with a metallic top cover lid. RF absorber material may be used on the inside surface of the top coverlid if required.

- The prime DC power shall be totally derived from a single supply with a voltage of up to +5 Volts DC or –5 Volts DC employing two wires. A metered power supply will be provided atIMS2013 by the organizers.

- No internal batteries may be used.

- No changes are allowed on the device during the measurements.
The amplifier must meet or exceed all of the above requirements, where the LNA with the highest LNA Figure of Merit (LNAFOM) will win the competition. The judges calculate the LNAFOM based on the following formula:

\[ \text{LNAFOM} = \frac{\text{LNAFOM}_{\text{up}} + \text{LNAFOM}_{\text{low}}}{2}, \]

\[ \text{LNAFOM}_{\text{low}} = \frac{\text{OIP3}_{\text{low}}/\text{Pdc}}{\text{NFdB}_{\text{low}}} \text{ (at 1.1GHz)}, \]

\[ \text{LNAFOM}_{\text{up}} = \frac{\text{OIP3}_{\text{up}}/\text{Pdc}}{\text{NFdB}_{\text{up}}} \text{ (at 1.6GHz)}, \]

\[ \text{NFdB}_{\text{up}}, \text{NFdB}_{\text{down}} \text{ is set to 1.5 dB for all contestants after the go/no-go decision,} \]

where:

\[ \text{LNAFOM}_{\text{up}}, \text{LNAFOM}_{\text{low}} = \text{LNA Figure of Merit in the lower and upper band}, \]

\[ \text{OIP3}_{\text{low}} = \text{Output third order intercept point IP3 of LNA in milliwatts for the lower tone (based on a two-tone measurement with tones at 1.12 GHz and 1.14 GHz with 20 MHz spacing and taking the lower IP3 at 1.10GHz)}, \]

\[ \text{OIP3}_{\text{up}} = \text{Output third order intercept point IP3 of LNA in milliwatts for the upper tone (based on a two-tone measurement with tones at 1.56 GHz and 1.58 GHz with 20 MHz spacing and taking the upper IP3 at 1.60GHz)}, \]

\[ \text{P}_{\text{DC}} = \text{DC power drawn by power supply in milliwatts}, \]

\[ \text{NFdB}_{\text{low}}, \text{NFdB}_{\text{up}} = \text{LNA noise figure in dB = 1.5 dB set for all those passing the test at 1.1 and 1.6 GHz}, \]

\[ \text{OIP3dBm}_{\text{low}} = \text{Po}_{\text{low}} + 0.5 \left( \text{Po}_{\text{low}} - \text{P3rd}_{\text{low}} \right), \]

\[ \text{OIP3dBm}_{\text{up}} = \text{Po}_{\text{up}} + 0.5 \left( \text{Po}_{\text{up}} - \text{P3rd}_{\text{up}} \right), \]

\[ \text{Po}_{\text{low}}, \text{Po}_{\text{up}} = \text{Output power of the 1.12 GHz and 1.58 GHz signal in dBm}, \]

\[ \text{P3rd}_{\text{low}}, \text{P3rd}_{\text{up}} = \text{Output power of the third order products at 1.1 GHz and 1.6 GHz in dBm}, \]

\[ \text{OIP3}_{\text{low}} = 10^{\left( \text{OIP3dBm}_{\text{low}}/10 \right)} \text{ in milliwatts for the lower tone}, \]

\[ \text{OIP3}_{\text{up}} = 10^{\left( \text{OIP3dBm}_{\text{up}}/10 \right)} \text{ in milliwatts for the lower and the upper tone}. \]

In the event of two contestants resulting in the same LNAFOM, the student with the lower DC voltage wins.
3.0 Requirements and Specifications

The low-noise amplifier needs to include some desirable marketing requirements for a successful profit. As seen in Table I, the module has five marketing requirements, including low voltage source, high third-order intercept point, low noise, high output power, and ruggedness. The low voltage source helps the module use a lower amount of power, which has become highly desirable in devices that run off a charge. The module also has the definition of highly linear; the third-order intercept point measures how linear the system has achieved. As described in the introduction, high frequency system’s components procure multiple sources of noise; therefore, the system needs to have a low noise figure. The signal from the satellite enters the low-noise amplifier before any analog-to-digital conversion occurs and for the ADC to get a sufficient reading, the signal needs to achieve a high enough power. Due to the frequency range of a GPS, this low-noise amplifier should achieve a wideband and needs ruggedness against other frequency spectrums.
### Table I: Marketing requirements and engineering specifications.

<table>
<thead>
<tr>
<th>No.</th>
<th>Marketing Requirements</th>
<th>Engineering Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-4</td>
<td>Use a maximum supply voltage of +5VDC.</td>
</tr>
<tr>
<td>2</td>
<td>3, 5</td>
<td>Operate between 1.1 and 1.6GHz.</td>
</tr>
<tr>
<td>3</td>
<td>1, 3</td>
<td>Have a maximum noise factor of 1.5dB over all operational frequencies.</td>
</tr>
<tr>
<td>4</td>
<td>1, 2, 4</td>
<td>Have an output power greater than -3dBm for all operational frequencies.</td>
</tr>
<tr>
<td>5</td>
<td>2, 3, 4</td>
<td>Amplify a small-signal by at least 13-dB with a source and load impedance of 50-Ohms over the band.</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>Contain shielding at the inputs and outputs.</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>Include 3.5mm SMA connectors (female at the input and male at the output).</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>Use two wires with banana plugs at least 0.5 meter in length for the power supply (red plug for positive and black for ground).</td>
</tr>
</tbody>
</table>

**Marketing Requirements**

1. Use a low voltage source.
2. Have high third-order intercept point.
3. Have low noise.
4. Have high output power.
5. Broadband.
6. Rugged.

The market requirements break down into more specific engineering specifications, which are also shown in Table I. The middle column lists the marketing requirements that derive the engineering specifications, where the specifications break down into more technical detail and more on what the device should look like. The first requirement defines the maximum input voltage of the low-noise amplifier, where the range from 0V to +5V is a typical range of voltage inputs for one transistor amplifiers. Input voltages over +5V could drive more power into the transistor than needed. Requirement two states the GPS frequency range, between 1.1GHz and 1.6GHz. A reasonable noise figure of 1.5dB still allows the low-noise amplifier to achieve enough gain without a corrupted output signal. The output also has needs enough power to drive the signal into the rest of the system, and 3dBm produces enough power to drive other modules within a GLONASS system. As stated in the introduction, a small-signal input needs amplification of a certain gain. The output
signal has to have a gain of at least 13dB for any other module to use the input signal. Requirements 8-9 describe the type of connectors used to measure the device.
4.0 Design

The block diagrams shown below visually describe the low-noise amplifier module. Table II provides a brief description of the level zero block diagram shown in Figure 1. Figure 1 includes the inputs labeled on the left side with the output on the right side. The carrier signal comes from the receiver of the device and the power supply involves the +5V input described in the engineering specifications. Amplifier output denotes the output to the rest of the system, a highly linear, low-noise, and amplified signal.

<table>
<thead>
<tr>
<th>Module</th>
<th>Broadband, Rugged, High Linearity, Low-Noise Amplifier Module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
</tr>
<tr>
<td>- Carrier Signal: Filtered SMA small-signal input of 1.1GHz to 1.6GHz</td>
<td></td>
</tr>
<tr>
<td>- Power Supply: +5V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
</tr>
<tr>
<td>- Amplified carrier signal</td>
<td></td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td>Amplifies the carrier signal by at least 13-dB with a low noise figure of 1.5-dB</td>
</tr>
</tbody>
</table>

Table II: Level zero block diagram breakdown.

The level one table and block diagram share a similar relationship as the ones above, only they represent a slightly lower level of description. Figure 2 shows the level one block diagram of the low noise amplifier, with Table III giving a description of the figure. The input carrier signal travels on a transmission line to the input matching sub-system that sets up the signal for amplification.
The amplifier block receives the input voltage supply of +5V to power the transistor and help amplify the signal. The output matching block receives the amplified signal through a transmission line from the amplifier block. The output matching block diagram includes matching of the input transmission block.

<table>
<thead>
<tr>
<th>Module</th>
<th>Broadband, Rugged, High Linearity, Low-Noise Amplifier Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs</td>
<td>- Carrier Signal: Filtered SMA small-signal input</td>
</tr>
<tr>
<td></td>
<td>- Power Supply: +5V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Intermediate Signals</td>
<td>-T1: Transmission line signals from input matching block to the amplifier block</td>
</tr>
<tr>
<td></td>
<td>-T2: Transmission line signals from the amplifier block and the output matching block</td>
</tr>
<tr>
<td>Outputs</td>
<td>- Amplified carrier signal</td>
</tr>
<tr>
<td>Functionality</td>
<td>Amplifies the carrier signal by at least 13-dB with a low noise figure of 1.5-dB</td>
</tr>
</tbody>
</table>

Table III: Level one block diagram breakdown.

The beginning of the design starts with the selection of a low-noise transistor that can meet the amplification and noise figure of the requirements. The design for this low-noise amplifier was done with Avago Technologies’ ATF-54143 enhancement mode low-noise transistor. The ATF-54143 has NF=0.55dB, Ga=17.4dB, P1dB=20.4dBm, and OIP3=36dBm at 3V, 60mA (2GHz) and...
varies just slightly at other DC biases other than 5V, 60mA. After choosing a transistor that worked well with the requirements needed, the S-Parameters were extracted from their data sheets to assist in finding the correct matching of the reflections.

<table>
<thead>
<tr>
<th>$S_{11}$</th>
<th>$S_{12}$</th>
<th>$S_{21}$</th>
<th>$S_{22}$</th>
<th>$K$</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.655(^\circ)-141.1</td>
<td>10.514(^\circ)-91.9</td>
<td>0.05(^\circ)-37.4</td>
<td>0.229(^\circ)-99.5</td>
<td>0.7736</td>
<td>0.543</td>
</tr>
</tbody>
</table>

Table IV: List of S-Parameters, $K$ and $\Delta$.

The S-Parameters for the ATF-54143 at 3V, 60mA, and 1.3GHz are shown in Table IV with the calculations for stability checking. It can be observed that the transistor is potentially unstable with $K<1$ and $|\Delta|<1$ where:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

And

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

Therefore, when designing the input and output stability, stability needs to be kept in mind. The stability graphs can be plotted to help avoid any issues when designing the matching networks. By graphing the input and output stability circles and plotting the constant gain circles, the $\Gamma_S$ and $\Gamma_L$ values can be obtained. First, to determine $\Gamma_L$, the input stability circles should be plotted in the $\Gamma_L$ plane. Since $S_{11}>1$ then the origin on the plot is the stable region. Plotting the gain circle is then place on the same plane, where Figure 3 below shows the $\Gamma_L$ value.
Along with $\Gamma_L$, the value for $\Gamma_S$ needs to be calculated for the output matching. To obtain a $\Gamma_S$ that is stable, the output stability circle is analyzed with the $S_{22}$ parameter. Same as the input side, the origin contains the stable region when plotting the output stability circle. After calculating the $\Gamma_L$, $\Gamma_S$ can be found using the following equation:

$$\Gamma_S^* = \Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

The $\Gamma_S$ values are then plotted with the output stability circles as shown in Figure 4. The green boxes are each numbered and the resulting value is then put into the command prompt in Matlab and shown in Figure 5.
Therefore, the target values are shown in Table V shown below, after changing them to polar values.

<table>
<thead>
<tr>
<th>$\Gamma_L$</th>
<th>$0.267 \angle 95.23^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_S$</td>
<td>$0.191 \angle 134.37^\circ$</td>
</tr>
</tbody>
</table>

Table V: Target values for matching design.

Using these values, the theoretical matching networks can be calculated. First, beginning with the input matching, the following lengths must be calculated shown in Figure 6, where $Z_0$ is 50Ω. The calculations on the smith chart were done with admittance values, so convert $\Gamma_S$ to admittance $\bar{y}_S$. 
The shunt-stubs can only introduce susceptance to the source impedance \((Z_0)\), thus moving along the \(g = 1\) circle. Also, movement from \(\bar{y}_A\) to \(\bar{y}_s\) is on the constant \(|\Gamma_s|\) circle (movement toward generator), this will constitute \(\ell_1\).

Begin by drawing the constant \(|\Gamma_s| = 0.191\) circle and locating where it intersects the \(g = 1\) circle. They should intersect twice and one of these points will constitute \(\bar{y}_A\). Since the value will then have to be rotated towards the generator, the value chosen was the one that had less to travel, giving a shorter stub length. Then, take half of the imaginary value and that is the balanced stub wavelength that is moved towards the generator. The following equation gives the balanced stub length.

\[
\ell_2 = 0.281\lambda - 0.25\lambda = 0.031\lambda
\]

Now to retrieve the \(\ell_1\) length by rotating from \(\bar{y}_A\) to \(\bar{y}_s\).

\[
\ell_1 = (0.5\lambda + 0.019\lambda) - 0.389\lambda = 0.13\lambda
\]

![Figure 6: Visual explanation of the input design lengths.](image)

Wavelengths are not physical lengths; therefore, the wavelength needs to be transformed to actual length with the following equation that gives \(\lambda\).

\[
\lambda = \frac{v_p}{f}, \text{where } v_p = \frac{c}{\sqrt{\varepsilon_r}}
\]

Therefore, using the same frequency used to gather the S-Parameters \((f = 1.3\text{GHz})\):
Thus, in inches the lengths are:

\[ \ell_1 = 0.13(5.86461\text{ inches}) = 0.762399 \text{ inches} \]
\[ \ell_2 = 0.031(5.86461\text{ inches}) = 0.181803 \text{ inches} \]

After the input matching lengths are calculated, the output matching can be done. Figure 7 shows the output matching and the values that need to be calculated. Begin the process by graphing the constant \(|\Gamma_L| = 0.267\) and find the intersections with the \(g = 1\) circle, there should be two points.

Figure 7: Visual explanation of the output design lengths.

There's a tradeoff in which point to choose for one point results in a shorter \(\ell_1\), but a longer \(\ell_2\). The decision on which point to choose can be changed based on what size requirements are present. Similar steps were done with the output matching as the input matching and found the following lengths.

\[ \ell_1 = (0.5\lambda + 0.293\lambda) - 0.397\lambda = 0.396\lambda \]
\[ \ell_2 = 0.36\lambda - 0.25\lambda = 0.11\lambda \]
\[ \ell_1 = 0.396(5.86461\text{ inches}) = 2.32239 \text{ inches} \]
$$\ell_2 = 0.11 (5.86461 \text{ inches}) = 0.645111 \text{ inches}$$

With the stub lengths, line lengths, and transistor the DC bias circuitry can be designed. The DC biasing for this low-noise amplifier was used from the ATF-54143 data sheet [5]. The design used a quarter wavelength transmission lines with shorted stubs instead of the RF chokes used from the data sheet. The values chosen for the resistors were based on getting the transistor biased at 3V and 60mA. Figure 8 shows the schematic used in the design.

![Figure 8: DC Bias schematic.](image)

Agilent ADS was used to simulate the low-noise amplifier. Figure 9 below shows the schematic of the low-noise amplifier, where the lengths of the stubs have been optimized based on the goals inputted into Agilent ADS.
Agilent ADS optimized the lengths of the stubs to obtain the largest third-order intercept, the gain to be greater than 13dB and noise figure to be less than 1.5dB. The following figures show the simulation results given from Agilent ADS.

The third order intercept was simulated and calculated based on a two-tone measurement, with the equations given in the background section. Figures 10 and 11 below show the two-tone measurement graphs for the upper and lower bands, respectively; and Table VI and VII below are the upper and lower band values of their respective graphs.
Figure 10: Lower band two-tone simulation.

<table>
<thead>
<tr>
<th>freq</th>
<th>Pout_dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00Hz</td>
<td>&lt;invalid&gt;</td>
</tr>
<tr>
<td>20000000.00Hz</td>
<td>-51.48</td>
</tr>
<tr>
<td>40000000.00Hz</td>
<td>-99.79</td>
</tr>
<tr>
<td>60000000.00Hz</td>
<td>-121.49</td>
</tr>
<tr>
<td>80000000.00Hz</td>
<td>-166.60</td>
</tr>
<tr>
<td>10000000.00Hz</td>
<td>-175.16</td>
</tr>
<tr>
<td>14000000.00Hz</td>
<td>-173.42</td>
</tr>
<tr>
<td>16000000.00Hz</td>
<td>-172.77</td>
</tr>
<tr>
<td>18000000.00Hz</td>
<td>-173.04</td>
</tr>
<tr>
<td>20000000.00Hz</td>
<td>-179.73</td>
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<tr>
<td>94000000.00Hz</td>
<td>-131.96</td>
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<td>96000000.00Hz</td>
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<td>98000000.00Hz</td>
<td>-125.90</td>
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<td>10000000.00Hz</td>
<td>-122.27</td>
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<td>10200000.00Hz</td>
<td>-118.30</td>
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<td>10400000.00Hz</td>
<td>-112.52</td>
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<td>10800000.00Hz</td>
<td>-78.51</td>
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<tr>
<td>11000000.00Hz</td>
<td>-34.97</td>
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<tr>
<td>11200000.00Hz</td>
<td>8.07</td>
</tr>
<tr>
<td>11400000.00Hz</td>
<td>7.75</td>
</tr>
<tr>
<td>11600000.00Hz</td>
<td>-35.48</td>
</tr>
</tbody>
</table>

Table VI: Data points corresponding to Figure 10.

The third-order intercept can then be calculated as stated in the background section shown below.

\[ OIP3dBm_{low} = 8.07 + 0.5(8.07 + 34.97) = 29.59 \text{ dBm} \]
This value gives the third-order intercept of the lower band that is later calculated in the LNAFOM.

\[ OIP3_{\text{low}} = 10^{(29.59/10)} = 909.9 \text{ mW} \]

The third-order intercept can then be calculated as stated in the background section shown below.
\[ OIP3dB_{\text{upper}} = 2.97 + 0.5(2.97 + 51.1) = 30.01 \text{ dBm} \]

\[ OIP3_{\text{upper}} = 10^{\left(\frac{30.01}{10}\right)} = 1002.3 \text{ mW} \]

This value gives the third-order intercept of the upper band that is later calculated in the LNAFOM. Figure 12 below shows the noise figure of the low-noise amplifier. The value is well below the requirement of 1.5dB at about 0.3dB on the lower band and 0.5dB at the upper band.

![Figure 12: Noise figure simulation.](image)

The gain of the amplifier is obtained from the \( S_{21} \) parameter, which is shown in Figure 13. The gain at the lower band is about 22.5dB and about 2.5dB at the upper band.
Figure 13: $S_{21}$ parameter, gain simulation.
5.0 Test Plan
There are several different tests needed to be done to ensure the requirements were met. Starting with the S-Parameters of the amplifier will give the gain results as well as some measurements to show if the amplifier is stable. The $S_{11}$ and $S_{22}$ parameters will show if the amplifier is stable by checking to see if the value is below 0. The $S_{21}$ parameter will give the gain of the amplifier.

After the S-Parameters are measured, the two-tone measurement uses two frequency generators, a power combiner, and a spectrum analyzer. One frequency generator is set to 1.12GHz/1.56GHz and the other 1.14GHz/1.58GHz both set to give a -20dBm at the amplifier input. However, there is a loss in the power combiner, so the $S_{21}$ parameter needs to be observed before the measurement. The spectrum analyzer will show a spike at $f_1$ (1.12GHz/1.56GHz), $f_2$ (1.14GHz/1.58GHz), and $2f_2-f_1$ (1.1GHz/1.6GHz).

The noise figure measure can be observed with a Vector Network Analyzer. The VNA has a BNC output on the back that is sent through an Agilent Noise Source and into the input of the amplifier. The output of the amplifier is shown through port 2 of the VNA.

The VNA can also be used to measure the 1dB compression point to check whether the amplifier exceeds the 3dBm requirement.
6.0 Development and Construction

Agilent ADS outputs a layout of the schematic that can be tweaked to any necessary conditions.

Agilent ADS then extracts a Gerber file that is used to fabricate the board. Figure 14 shown below is a viewing of the Gerber file that later became a circuit board.

![Figure 14: Viewing of the Gerber File.](image)

After the board goes through the fabricating process, the board will look as shown in Figure 15.
After proper fabrication the components can then be soldered onto the board. The final product of this amplifier is shown in full below in Figure 16.
7.0 Test Results
The first test on the amplifier was the S-Parameters on the VNA. The log-magnitude plots were taken for all the S-Parameters. The $S_{11}$ parameter is observed in Figure 17 and shows good results, with the values over the band falling under 0dB. Also, the $S_{22}$ parameter, shown in Figure 18, includes all the values below 0dB, showing the amplifier is stable. $S_{21}$, as stated before, gives the forward gain of the amplifier and $S_{12}$ gives the reverse isolation, these are shown in Figures 19 and 20, respectively.

Figure 17: $S_{11}$ parameter of amplifier.
Figure 18: $S_{22}$ parameter of the amplifier.

Figure 19: $S_{21}$ parameter and gain of the amplifier.
Observing the $S_{21}$ parameter, the gain is 19.1 dB at the lower band and 17.2 dB at the upper band. This is slightly lower than expected from simulation; however, the simulation was based on lossless transmission lines. Therefore, there was bound to be some loss in the gain.

After measuring the S-Parameters, the third-order intercept was evaluated using a two-tone measurement. Starting with the lower band, the equipment was set-up as defined in the previous test plan section. Figure 21 shows the $S_{21}$ parameter, showing a drop in gain. This was incorporated in accurately getting the -20dBm power into the input of the amplifier. Since the power combiner has loss, that power amount had to be compensated in the output of the frequency generators.
Figure 21: $S_{21}$ parameter and attenuation of the power combiner.

When the power is set to -20dBm at the input of the amplifier at both of the frequencies, then the spectrum analyzer output can be observed, which is shown in Figure 22.

Figure 22: Lower band two-tone measurement.
The lower band third-order intercept can be calculated based on the values shown in Figure 22. The calculation is shown below.

\[
OIP3dBm_{low} = -0.35 + 0.5(-0.35 + 56.74) = 27.84 \text{ dBm}
\]

\[
OIP3_{low} = 10^{\frac{27.84}{10}} = 608.8 \text{ mW}
\]

The third-order intercept is much lower than anticipated for the lower band. The upper band’s third-order intercept is shown in Figure 23 below.

Figure 23: Upper band two-tone measurement.

Using the data found in Figure 23, the third-order intercept can be calculated, which is shown below.

\[
OIP3dBm_{up} = -1.48 + 0.5(-1.48 + 62.03) = 28.79 \text{ dBm}
\]

\[
OIP3_{up} = 10^{\frac{28.79}{10}} = 757.7 \text{ mW}
\]
Next, the noise figure of the low-noise amplifier is checked against the requirements. The VNA measurement for the noise figure is shown in Figure 24. The red line on the graph shows the gain of the amplifier, while the yellow line represents the noise figure of the amplifier.

![Figure 24: Noise figure measurement.](image)

The noise figure of the amplifier appears to meet the requirements for the frequency band, with a 0.902dB noise figure at the lower band and 0.714dB for the upper band. This provides an effective amount of low-noise to the system.

With the data from above, the LNA Figure of Merit of this amplifier can be evaluated. The noise figure meets the 1.5dB requirement, so when calculating Figure of Merit use 1.5dB. The third-order intercepts at the lower band and upper band were 608.8mW and 757.7mW, respectively. Finally, the DC power consisted of a 5V\textsubscript{DC} rail that pulled 64mA into the system, giving a P\textsubscript{DC} a value of 320mW. Therefore, the following shows the LNAFOM calculation.

\[
LNAFOM_{\text{low}} = \frac{OIP_{3\text{low}}}{P_{\text{DC}}xNF\text{(dB)}} = \frac{608.8}{320\times1.5} = 1.27
\]
Thus, giving a final LNA Figure of Merit of 1.43.

Figure 25 below shows the 1dB compression point measurement, where the output power at the 1dB compression point is -2.58dBm. This is the point where the amplifier begins to amplify at a lower percentage of its capability.
8.0 Conclusion

The low-noise amplifier in this report met or exceeded all the requirements needed to effectively be integrated with a current GLONASS GPS system. The final gain of the amplifier was with 17-20dB, which really comes from the choice of transistor. Third-order intercept had no requirements but to be the highest possible to count more for the LNA Figure of Merit. The amplifier reached a third order intercept of 608.8mW and 757.7mW for the lower and upper bands, respectively. Noise figure, a large part of the project, stayed below the 1.5dB requirement for the entire bandwidth.

The amplifier met most of its expected results with only a few measurements. The noise figure in simulation was much lower than measured, mainly because the use of a through-hole lengthy resistor. The spacing for the 50Ω resistor was not any good size for a surface mount chip resistor; however, the requirement was still met. Third-order intercept wasn’t off too much from the expected, but after factoring in lead lengths and the real properties of the transistor, the linearity drops a bit. The drop in gain is due to the simulation runs being with lossless transmission lines, and after the actual loss in the transmission lines had an affect the gain fell.
9.0 References


10. Appendices

Appendix A

Project title: Broadband, Rugged, High Linearity, Low-Noise Amplifier

Students Name: Shane Smith

Advisor’s Name: Dennis Derickson

• Summary of Functional Requirements

This report examines the application of a low-noise amplifier module for a Global Positioning System (GPS). This low-noise amplifier module helps allow the carrier signal to get the amplification needed to give a smoother analog to digital conversion. However, the frequency range of the GPS spectrum reaches up to 1.6GHz, where component noise becomes an issue and can create a disrupted signal. This low-noise amplifier needs to create a reasonable gain, while achieving a low noise figure. An amplifier with high gain and low noise figure becomes difficult because they create a design trade-off, higher the gain brings higher the noise figure. This report shows the trade-offs of gain and noise figure and a way of designing a reasonable amplifier for higher frequencies. See section 2 of this report for more details on requirements and specifications.

• Primary Constraints

Any low-noise amplifier has difficulties with key trade-offs. A low-noise amplifier needs to achieve a high gain, as well as a low noise figure; this causes a difficulty when the two variables affect each other's performance. During design, simulation and testing the two performances need careful monitoring to ensure all functional specifications meet the ones described in chapter 2 of this report. Also, the input voltage variable has an impact on the overall output power. The design limitations on maximum input voltage causes other trade-offs with gain, output power, and input power. The frequency range poses an impact on the design due to the interference of RF signals; which also results in the consideration of wire length and shielding connections.

• Economy

The low-noise amplifier impacts the economy in several different areas. Labor costs need analyzing and consideration for economic impacts from human capital. The labor costs combine of research, development, design, build, test and manufacturability. There currently exists a market of low-noise amplifiers in Global Positioning Systems and this project results in means of competition to those existing modules. The instruments used throughout the process of this project may include vector network analyzer, spectrum analyzer, oscilloscope, voltmeter, amp-meter, power supplies, soldering iron, and magnifying glass. There exist many of Earth’s resources in this project due the ample amount consumed in a project due to the large quantities of products built. The components within this project consume resources, such as silicon, copper, polymers, and solder.
The project requires planning, research, and development that all result in a cost that comes from the initial designer. While experimenting with new designs the cost of power inputs and electricity needs to come from the user of the equipment. The benefits of the project grow once the product appears on the market and after the beginning of manufacturing. These benefits include a large quantity due to the high volume of these modules in the market, where the beneficiaries go to the stakeholders in this product. The product prototype emerges in the month of June in 2013 and the product needs to last for two years on the market before better technology arises. Table VIII below breaks down the allotted time allowed for the project. Table IX below shows the estimated costs of the project for the first prototype.

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Table VIII: Gantt chart of project scheduling.

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<th>Quantity</th>
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Table IX: Billing materials.

- If manufactured on a commercial basis

With over 15.1 million GPS units sold in the US in 2008 alone, the projected amount of units sold in a year could reach a million, when factoring in competition for low-noise amplifier modules. Since commercialized components are about $0.01 with the purchases in high volume the projected cost of each unit could be about $4.50 and sold in the market for $9 each to account for manufacturing
costs and for profit. This results in a projected profit of $4.5 million dollars per year. Cost start to occur at the start of development and profit begins at the start of distribution.

- **Environmental**

For this project to move forward in the current market, the environment may need to suffer for the production. From a manufacturing standpoint, the project impacts greenhouse gas emissions, which is contributing to the heating of the Earth. Also, during the building of devices the extra waste may not always be recyclable and would be taking resources from the Earth without replenishing natural resources. The scope of the project consumes mostly silicon extracted from sand and can impact the environment of beaches, lakes, and rivers. These ecosystems could see impact from the project and harm the living environments for different reptilian species. Also, due to the low-noise amplifier integrating into a GPS device, there can be more exploration of different habitats. This extra exploration could impact the natural habitats of wildlife, since a GPS allows for safer travel. End of product environmental impacts mentioned in the sustainability section of this appendix.

- **Manufacturability**

Due to the project's overall size and dimensions, manufacturing high volume of these products could pose an issue. The low-noise amplifier module needs skilled workers to perform the soldering of surface mount components. With a device that needs careful attention, it can be difficult to produce a product in high volume in short amounts of time. The market shows a large population of people who own some type of GPS device; therefore, the demand for these low-noise amplifier modules for GPS devices is high.

- **Sustainability**

Since the low-noise amplifier integrates with a GPS device, there will be a large volume of resources used. Since the device consumes a high volume of resources, the environment may not be capable of replenishing these resources as they're used. Also, since much of technology dispensed by consumers comes so easily, the waste of this product could be high without recycling. Large waste results in an unsustainable future, where the Earth cannot replenish the resources consumed. The project utilizes only one transistor and the rest comprise of commercialized components. The design could improve to a more sustainable product, if it utilized only one chip where the commercial components embed in the chip. This would allow for less use of resources, as well as a smaller size design, but could come at a higher cost.

- **Ethical**

The impact of this project, from an ethical view, shows a basis of utilitarian thinking. The project comes at a low cost possible for greatest profit. This type of framework causes an issue where the quality of the product becomes diminished and customer satisfaction may decline. Low quality devices typically come from a design that has lower reliability components, to lower cost. With a product based on low-cost, the customer is happy with a small cost to them; however, they pay that price with a possibly lower quality and less reliable product. The product impacts the ethics of
affecting the environment and the safety of it. Due to the use of resources, the environment could suffer without replenishment of used resources.

IEEE Code of Ethics states that as an engineer, to accept responsibility in making decisions consistent with the safety, health and welfare of the public. Misuses of this product can disregard this code of ethics. Many consumers of GPS systems use them while driving and inadvertently cause accidents. Also, hikers and travelers often use GPS systems to prevent them from getting lost; therefore, the low-noise amplifier cannot fail so that travelers don’t get lost. This product cannot allow consumers left into dangerous situations.

• Health and Safety

During the manufacturing process of the project, a possibility of injury becomes high. Due to the need of soldering, high temperature burns and breathing in the burning solder can lead to serious and long term injuries. Shipping devices can lead to possible injuries with vehicle accidents and other type of crashes. The hard labor of manufacturing and shipping can lead to long term bodily aches, joint injuries, and other bodily injuries. The use of the product can lead to accidents if misused because the device creates a guide to places people might not travel to otherwise. One application of a GPS device is during travel in a vehicle, and if misused during the act of driving could lead to an accident.

• Social and Political

High cost of manufacturing in the United States of America could result in outsourcing to other countries. With more outsourcing to other countries, the US has fewer jobs available for citizens. Outsourcing has created a huge debate during Presidential Elections the past few runs, and this project contributes to that aspect. The project has the potential to affect every US voter because of the rising issue of outsourcing. Also, the investors and purchasers of GPS devices become stakeholders in this project because they give into this project’s profitability. If a product does not work properly, it may result in harm to the stakeholder as the device could direct them in the wrong direction. The indirect stakeholders of this project are the ones who require similar resources may have issues finding similar sources. The direct stakeholders from this project include investors involved in GLONASS system products; while some indirect stakeholders include those invested in other GPS type systems.

• Development

The project requires special techniques for optimal performance due to the concentration in RF signals and high-frequency amplification. The use of gain circles, smith charts, and vector network analyzers have helped the overall understanding of high frequency amplifier design. The following literature search helped with the understanding of this report and the project.


