

Optimizing Antenna-LNA T_{SYS} Performance by Transmission Line Matching

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Abstract

The first rule for amateur radio telescope builders is to maximize sensitivity by connecting the low noise amplifier (LNA) directly to the antenna; maybe via a low-loss band-defining filter. However, this is not always the best strategy, especially if the antenna and/or the LNA impedances are not well matched and even moderately reactive [1]. In Reference 1, it is shown that resistive mismatches are responsible for added thermal noise and that reactive mismatches reduce the available power. In these cases, the professional solution is to design a specific matching circuit. A simpler alternative for amateurs is to use a short length of transmission line as an impedance transformer to improve the antenna-LNA match. The advantages of matching, include maximizing power transfer from the antenna to the LNA and also minimizing resistive mismatch noise - a double whammy improvement! With available cheap Vector Network/Antenna Analyzers (VNA), amateurs can easily measure RF component complex impedances to underpin transmission line length calculation.

Introduction

Maximum power is transferred from a matched antenna to a following LNA when the LNA load resistance is equal to that of the antenna. When the source and load are unmatched but purely resistive, there is a mismatch power loss which both attenuates the wanted signal and in addition produces extra thermal noise. With reactive source and load components, the presence of the reactance reduces the load current, which in turn reduces the available power to the LNA, but generates no extra noise. With combined resistive and reactive source and load components, the result is less predictable, producing both mismatch loss and reduction in available power. An example in Reference 1 showed that by improving the match in a practical case by using a quarter-wave transmission line transformer, the resistive mismatch noise was much improved. This article explores the use of a calculated length of transmission line between the antenna and LNA, acting as an impedance transformer, in an attempt to optimize the RF path match and improve the system noise temperature T_{SYS} . A Python computer program using the transmission line equations is appended; by inserting measured system impedance values and running the program in a Python integrated development environment (IDE), it outputs data and graphical plots from which the optimum transmission line length can be chosen to minimize the system T_{SYS} . The line insertion loss is small as its electrical length is invariably less than half a wavelength at the design center frequency.

The Problem

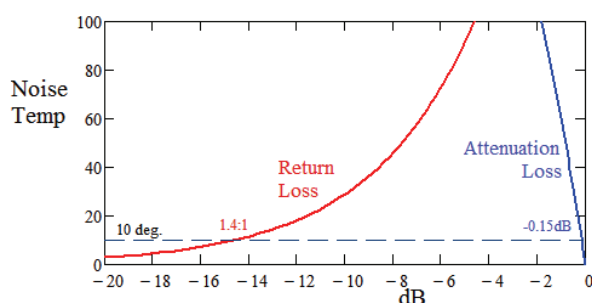


Figure 1. Attenuation and Mismatch (Return Loss) Contribution to T_{SYS} Noise Temperature

Typical radiometer antennas and LNAs will have match specifications with voltage standing wave ratios (VSWRs) in the region 1.5 to 2.0 when measured in a 50 ohm transmission line. The corresponding return loss range is -14dB to -9.5dB.

Figure 1 shows that with even modest attenuation or mismatch system specifications, these losses can have quite a large effect on the system noise temperature T_{SYS} .

The standard form of the radiometer system noise equation is,

$$T_{SYS} = A(1 - \rho^2)T_s + [1 - A(1 - \rho^2)]T_a + T_{LNA} \quad (1)$$

Where, A is the antenna-LNA connection power loss factor (connector attenuation) and ρ is the voltage reflection coefficient at the antenna terminal ($\rho = |(z_s - z_l)/(z_s + z_l)|$), where z_s and z_l are the source and load impedances). ρ^2 is a measure of the return loss ($10 \cdot \log(\rho^2)$, in dB). T_{LNA} is the LNA noise temperature and T_a is the ambient temperature ($= 290$ °K)

Equation 1 implies that both signal attenuation and mismatch noise increase with junction mismatch and attempts to improve the RF chain match to reduce ρ could pay dividends.

This equation is strictly only true if neither the antenna nor the LNA have any reactance components. The equation modification where there is significant reactance components is analyzed in the following sections culminating in a modified T_{SYS} formula, Equation 6.

RF Analysis

a) Direct Antenna-LNA Connection

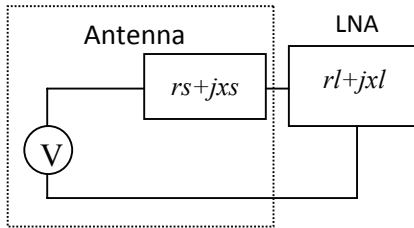


Figure 2. Antenna-LNA Direct connection

From Figure 2, for direct antenna-LNA connection and with the antenna complex source impedance, $z_s = r_s + jx_s$ and LNA complex load impedance $z_l = r_l + jx_l$, the power absorbed by the load resistance component, calculated using basic circuit theory, is given by [2],

$$P_{rl} = \frac{V^2 r_l}{(r_s + r_l)^2 + (x_s + x_l)^2} \quad (2)$$

and the maximum available power with reactance occurs when,

$r_l^2 = r_s^2 + (x_s + x_l)^2$, so that the available power now is,

$$P_{availX} = \frac{V^2 \sqrt{r_s^2 + (x_s + x_l)^2}}{\left(r_s + \sqrt{r_s^2 + (x_s + x_l)^2}\right)^2 + (x_s + x_l)^2} \quad (3)$$

The ratio of the power absorbed by the load resistance to the maximum available power with zero reactance is the attenuation loss factor,

$$A_{Mloss} = \frac{4 r_l r_s}{(r_s + r_l)^2 + (x_s + x_l)^2} \quad (4)$$

This is equivalent to the transmission line power ratio, $1 - |\rho|^2$, where ρ is the complex voltage reflection coefficient. It includes the resistive mismatch loss and the available power loss due to the reactance.

The ratio of the power absorbed by the load resistance to the available power with reactance is a measure of the circuit resistive mismatch attenuation loss factor and is given by,

$$\frac{P_{rl}}{P_{availX}} = A_{rLX} = \frac{2rl \left(rs + \sqrt{rs^2 + (xs + xl)^2} \right)}{(rs + rl)^2 + (xs + xl)^2} \quad (5)$$

The effect of reactance components in the source and load is summarized in Figure 3.

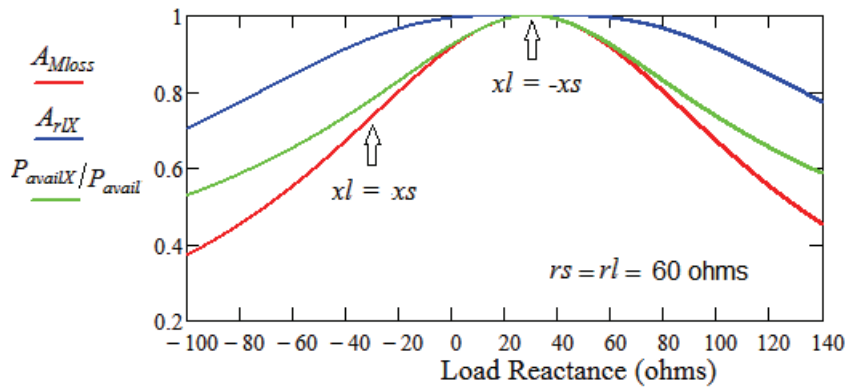


Figure 3. Loss v Load Reactance; Total loss (red), Available Power (green), Resistive Mismatch Loss (blue)

Figure 3 is derived from Equations 3, 4 and 5 and plotted as a function of the load reactance. For this example, the antenna impedance is, $60 - j30 \Omega$ and the LNA impedance given by $60 + jxl \Omega$, where xl is varied over Figure 3 x-axis range. It shows that unbalanced source and load reactance (away from $xl = -xs$), reduces the available power for the load and indicates the reactive portion of return loss (Equation 5) that does not contribute to the system noise.

Note that the red curve is equivalent to the transmission line return loss measure and that the blue curve (resistive mismatch) and the green curve (available power loss due to reactance) represent its real and reactance components. In this example, with equal resistive components, optimum match occurs when the reactive components cancel and clearly demonstrates that large reactance unbalance is to be avoided.

Using the information from this section, by separating the complex impedance loss factor components, T_{SYS} of Equation 1 modifies to,

$$T_{SYS} = A.A_{Mloss}.T_S + [1 - A.A_{rLX}]T_a + T_{LNA} \quad (6)$$

In practice, there are other noise sources collected by the antenna including, sky noise, T_{sky} , cosmic microwave background, T_{CMB} , and spillover/side or back-lobe noise, T_{Spill} that also contribute to T_{SYS} . These are in turn attenuated with the wanted signal T_S by the loss factors: $A.A_{Mloss}$

An indicative measure of the working target signal-to-noise ratio (SNR) is,

$$SNR = \frac{A.A_{Mloss} \cdot T_S}{(1 - A.A_{rLX})T_a + T_{LNA} + A.A_{Mloss}(T_{sky} + T_{CMB} + T_{spill})} \quad (7)$$

b) Transmission Line Antenna-LNA Connection

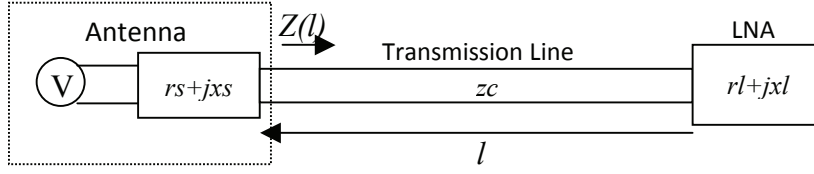


Figure 4. Antenna-LNA Transmission Line Connection

Inserting a loss-less transmission line, length l , characteristic impedance zc terminated by a load zl , the line input impedance (Figure 4), is given by,

$$Z(l) = zc \left[\frac{\frac{zl + zc}{2} e^{j\frac{2\pi fl}{c}} + \frac{zl - zc}{2} e^{-j\frac{2\pi fl}{c}}}{\frac{zl + zc}{2} e^{j\frac{2\pi fl}{c}} - \frac{zl - zc}{2} e^{-j\frac{2\pi fl}{c}}} \right] \quad (8)$$

where, $zl = rl + jxl$

and, f is the signal frequency

The voltage and current along the line length l , measured from the load is given by,

$$V(l) = il \left[\frac{zl + zc}{2} e^{j\frac{2\pi fl}{c}} + \frac{zl - zc}{2} e^{-j\frac{2\pi fl}{c}} \right] \quad (9)$$

$$I(l) = \frac{il}{zc} \left[\frac{zl + zc}{2} e^{j\frac{2\pi fl}{c}} - \frac{zl - zc}{2} e^{-j\frac{2\pi fl}{c}} \right] \quad (10)$$

$V(l)$, describes the voltage standing wave and the load current il is given by,

$$il = \frac{Z(l)}{zs + Z(l)} \left[\frac{1}{\frac{zl + zc}{2} e^{j\frac{2\pi fl}{c}} + \frac{zl - zc}{2} e^{-j\frac{2\pi fl}{c}}} \right] \quad (11)$$

where, $zs = rs + jxs$

The available power with reactance terms (Equation 3) now becomes,

$$P_{availX} = \frac{V^2 \sqrt{rs^2 + [xs + \text{Im}(Z(l))]^2}}{\left(rs + \sqrt{rs^2 + [xs + \text{Im}(Z(l))]^2} \right)^2 + [xs + \text{Im}(Z(l))]^2} \quad (12)$$

Equations 4 and 5 are similarly modified with rl and xl replaced by the real part of $Z(l)$, ($\text{Re}(Z(l))$) and the imaginary (reactance) part of $Z(l)$, ($\text{Im}(Z(l))$), respectively.

A property of a transmission line loaded with a complex impedance is that both the input impedance magnitude and vector argument (phase) varies as a function of the transmission line length and tuning the length for best match provides a useful alternative to bespoke matching circuits.

Application

Traditionally, understanding reflections at microwave junctions and optimizing microwave circuit performance with matching circuits uses the Smith Chart but for this article a Python 3 program (see Appendix) has been written exploiting the transmission line equations above to facilitate evaluation and optimizing the antenna - LNA match. For antenna complex impedance values, either a Vector Network Analyzer or the Vector Antenna Analyzer (Figure 5) are suitable.



Figure 5. Vector Antenna Analyzer Type: N1201SA

The test example offered in Reference 1 is repeated here, but instead of using the case of applying a quarter-wave transformer, the analysis considers the response for arbitrary lengths of intermediate transmission line up to half a wavelength.

Reference 1 Example: T_{SYS} Noise Calculations with Intermediate Transmission line.

For this example, consider using a LNA with 0.4 dB noise figure (with an input VSWR of 1.8 at 50 Ω characteristic impedance, connected to the antenna with a connector loss of 0.2 dB.

The Mini-Circuits ZX60P33U LNA input impedance at 600 MHz is, $30.8 - j13.5 \Omega$.

The antenna measured VSWR is 1.5 and the antenna source impedance is $62.5 + j20 \Omega$.

The ambient temperature, T_a is assumed to be 290° K.

In this case, analyze the system with an arbitrary length transmission line up to half a wavelength.

Before the Python analysis program *matchplot.py* (see Appendix) is run, it is user-initialized by changing the default parameters in lines 17 to 24. These are currently set to the above example figures.

Spyder *matchplot.py*; **Input data** - ADJUST IN PROGRAM TO SUIT

```

zc = 50                ## Line characteristic impedance (ohms)
zl = 31.8 - 1j*13.5   ## Source (antenna) impedance (ohms)
zs = 62.5 + 1j*20     ## Load (LNA) impedance (ohms)
f = 600000000         ## Radiometer center frequency (Hz)
Atten_dB = 0.2        ## RF chain attenuation/loss (dB)
LNA_dB = 0.4          ## LNA noise figure (dB)
Tsky = 15             ## Sky temperature
    
```

Running the program in the *Spyder IDE* with these figures, the graphical output is shown in Figure 6.

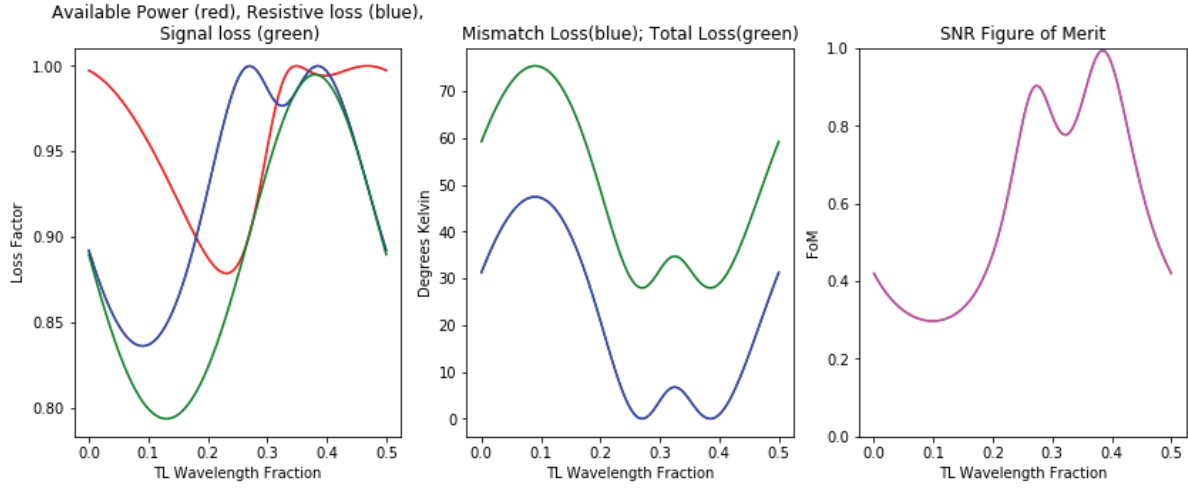


Figure 6. Example Results: Power Loss Factors and Resistive Noise Temperature

In Figure 6, the x-axis plots the transmission line electrical length over the range 0 to half a wavelength. Note the x-axis zero corresponds to direct antenna-LNA connection.

Notes:

In the left hand plot, the **red** curve records the available power from the antenna including the path attenuation as a ratio of the maximum, occurring when the source and load resistances are equal and the reactance parts cancel (Equation 2).

The **blue** plot indicates the mismatch real power loss factor from which the resistive noise temperature can be calculated.

The product of the available power and the resistive mismatch loss factors indicates the expected signal attenuation factor (**green**) due to the total mismatch return loss.

In the center plot, The **blue** curve indicates the resistive mismatch noise temperature in T_{SYS} and clearly indicates that a transmission line of 0.27 or 0.38 wavelengths will optimize the system performance. The **green** curve indicates the total noise temperature level, including the LNA, and contributions from the antenna-LNA attenuation, plus sky, CMB and spillover/sidelob/backlobe noise estimates.

The right hand **magenta** plot displays an SNR figure of merit (FoM) plot which indicates the advantage of the optimum transmission line of 0.38 times the signal wavelength over direct antenna LNA connection (equivalent to the measure at the zero length ordinate).

The FoM is defined as the SNR from Equation 7 divided by the SNR with no mismatch loss, i.e with $A_{Loss} = 1$ in Equations 6 and 7. So at 0.38 x wavelength the antenna-LNA are fully matched in this example (only the physical loss A and its noise contribution remain) and the fully matched T_{SYS} (Equation 6) becomes,

$$T_{SYS} = A(T_S + T_{sky} + T_{CMB} + T_{Spill}) + [1 - A]T_a + T_{LNA} \quad (13)$$

It is interesting to note from Figure 6, that the original guess of a quarter-wave transformer line, fortuitously found a region of improved performance.

Referring back to the red, green and blue curves in the first plot, with 0.38 wavelengths of 50 Ω transmission line between the antenna and LNA, the overall T_{SYS} performance will ensure the maximum available source power and virtually zero resistive mismatch noise.

Spyder *matchplot.py*; **Output Data:**

Input Data:

zc= 50 zs= (62.5+20j) zl= (31.8-13.5j) f= 600.0 MHz

loss: = 0.2 dB, LNA_noise = 27.978 deg K

Tsky etc: = 15.0 deg K, Tspill = 20.0 deg K.

The finer version of Table 1 (with user variable N=50 data increments, output by the program) and the Figure 6 plots indicate that optimum performance and minimum resistive mismatch noise, equivalent to an added noise temperature of <0.1 °K, occurs when the transmission line length is 0.38 wavelengths long and 95% of the available power from the antenna is passed to the LNA including the connection attenuation loss.

The transmission line cable actual physical length depends upon the cable choice velocity factor.

For comparison, with direct antenna-LNA connection (line length = zero) the resistive mismatch noise adds >32 °K to T_{SYS} .

TL Length /Lambda	Mismatch Temp:	Available Power Ratio	Return Loss Factor	Figure of Merit
0.0	31.266	0.952	0.849	0.658
0.049	43.945	0.937	0.795	0.559
0.099	47.265	0.912	0.763	0.527
0.149	39.291	0.879	0.76	0.563
0.199	20.993	0.848	0.786	0.692
0.249	2.333	0.843	0.836	0.899
0.299	3.849	0.909	0.897	0.918
0.349	4.056	0.954	0.941	0.942
0.399	0.913	0.949	0.946	0.983
0.449	13.804	0.954	0.908	0.823

Table 1. Optimum Transmission Line Length Search Summary (N=10)

Short Cut

With the aid of a plotting math package, the optimum line lengths can be found quickly by referring to the derivation of Equation 3, where from differentiating Equation 2, the maximum available power with reactance occurs when

$$rl^2 = rs^2 + (xs + xl)^2 \quad (14)$$

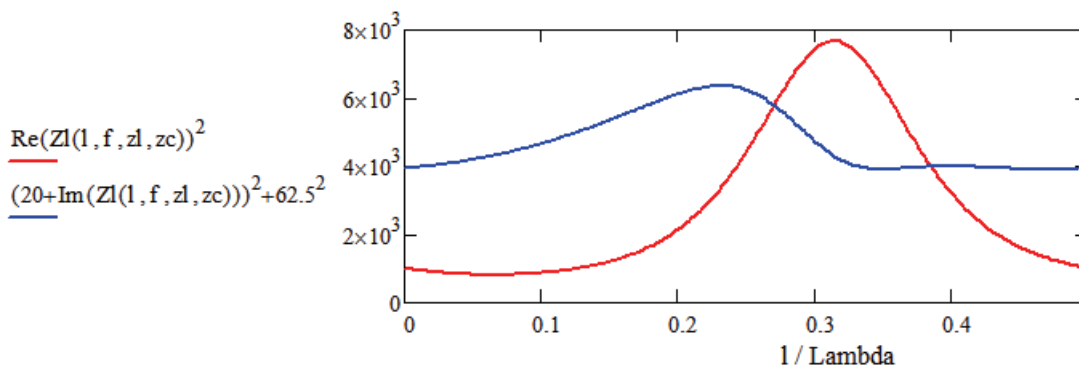


Figure 7. Confirmation of Optimum Transmission Line Lengths.

With the transmission line inserted between the antenna and LNA, the transmission line LNA load r_l becomes $Re(Z(l))$ and the reactive load x_l at the transmission line input becomes $Im(Z(l))$. Plotting Equation 14 equality in Figure 7, where they cross confirms the optimum peak lengths noted in Figure 6. The source antenna impedance is $62.5 + j20 \Omega$. The crossing points are at $l/\lambda = 0.27$ and 0.38 ; (λ is the wavelength at the band center frequency). Unfortunately, this simple short-cut does not identify which of the two is the best line length. Figure 7 indicates that the line resistive and reactance components vary over a wide range as a function of line length and it is this property that improves the probability of matching/balancing the corresponding components of the antenna.

Practicalities

There are a few practical considerations in implementing this T_{SYS} optimization method, apart from developing the skill to terminate correctly the required length of RF cable.

1. Not all VNAs provide the impedance information as required here - some reminders on typical measures and transformations...
 - a). *Magnitude + phase*: $Z \angle \phi \rightarrow r + jx = Z \cdot \cos(\phi) + jZ \cdot \sin(\phi)$;
 - b). *Magnitude + Inductance/Capacitance*: $x_L = 2\pi f L$; $x_C = -1/(2\pi f C)$;
 $\phi = \arcsin(x/Z)$; $r = Z \cos(\phi)$
- c). *Complex S-parameter*, $S_{11} = s_{real} + js_{imag}$; $Z_{in} = Z_C(1 - S_{11})/(1 + S_{11})$; Z_C is line characteristic impedance (50Ω). The complex division is best done with a math package, but if not available, here is the long-hand version:- $\left(\frac{a + jb}{c + jd} = \frac{ac + bd}{c^2 + d^2} + j \frac{bc - ad}{c^2 + d^2} \right)$.
2. For antenna impedance measurement, it is best to point the antenna to the sky and measure a few points over the operating bandwidth.
3. For LNA input impedance measurements, the recommendation is to use an attenuator (at least 10 dB to lower the VNA input power to avoid over driving. Most VNAs will need recalibration. For some suppliers, Minicircuits for example, they will have detailed input impedance information for their products available on their website.
4. Failing all these complications, a handy alternative is to make up a few odd lengths of cable up to half a wavelength and use the Y-factor T_{SYS} measurement method to determine the optimum cable length. Fine length adjustment might be possible using a few male and female connectors but beware, unless very high quality, each may have an associated insertion loss.

Conclusions

The usual advice to connect the LNA directly to the antenna terminal is questionable, as most practical RF components (antennas/filters/LNAs) exhibit complex impedances which can seriously affect the observed system sensitivity unless correctly matched. This article has shown that in situations where it is not possible or feasible to exactly match components or design a specific matching circuit, that by using a length of transmission line as a general purpose impedance transformer, it is possible to choose a line length that optimizes the transfer of power between an antenna and LNA.

Whilst the optimum line length can be obtained by the Python program the length tolerance based on a variety of source/load complex impedance trials, appears variable. As may be the antenna and LNA impedance variation over their operating bandwidths. Usually for very broadband LNAs, the range of complex impedance variation across a narrow band may not be significant but this may not be true for amateur antenna feeds. This therefore needs to be carefully checked.

This technique appears a very worthwhile consideration for amateur radio telescope constructors as it can significantly reduce resistive mismatch noise whilst having little impact on the wanted signal level (compare Equations 1 and 6).

References

1. East PW, Investigating the Radiometer Tsys Double Whammy Formula, Journal of the Society of Amateur Astronomers, September/October, 2023/
2. Doerry AW, Noise and Noise Figure for Radar Receivers, Sandia National Laboratories Report: SAND2016-9649, October 2016. <https://www.osti.gov/servlets/purl/1562649>

Appendix: Python Program

This program was developed using the Spyder IDE which is part of the Anaconda software distribution available from: <https://docs.anaconda.com/free/anaconda/install/windows/>
Although every care has been taken in producing this program it is not guaranteed and its use is entirely at the discretion of the user.

The following program listing can be 'copied', 'pasted' in Notebook, saved as *matchplot.py* and run in Spyder with user data entered in the program lines 17 to 24. Alternatively it can be downloaded from: <http://y1pwe.co.uk/RAProgs/matchplot.py>

Note that complex impedances in Python are written : $a + 1j*b$ where a and b are the component impedance resistance and reactance numerical values, in ohms.

The output plots are found in the working directory in the file: *Graphs.png*

matchplot.py Listing:

```
##matchplot.py
"""
author: PWE
Spyder Python 3.7
"""

import matplotlib.pyplot as plt
import numpy as np
import time
timestr=time.strftime("%d %m %Y")
print (timestr)

N = 50 # number of data increments
def rnd(z): # definition rounds data to 3 dec places
    return float(int(1000*z))/1000

    ## Input data - ADJUST TO SUIT
zc = 50 # Line characteristic impedance (ohms)
zl = 31.8 - 1j*13.5 # Source (antenna) impedance (ohms)
zs = 62.5 + 1j*20 # Load (LNA) impedance (ohms)
f = 600000000 # Radiometer Centre Frequency (Hz)
Atten_dB = 0.2 # RF chain loss (dB)
LNA_dB = 0.4 # LNA noise figure (dB)
Tsky = 15 # Sky+CMB temperature
Tspill = 20 # Spillover or Side/backlobe temperature
Tslos = 1-(Tsky + Tspill)/290 # equivalent sky/spill loss factor
A = 10**(-Atten_dB/10) #attenuation loss factor
Tlna = ((10**((LNA_dB/10)-1)*290) #LNA equivalent temperature

# Print input data table
print ('\n Input Data:')
print ('zc=',zc,' zs=',zs,' zl=',zl,' f=',f/1000000,'MHz')
```

```

print ('loss: = ', rnd(Atten_dB),'dB, LNA_noise = ', rnd(Tlna), 'deg K' )
print ('Tsky etc: = ', rnd(Tsky),'deg K   Tspill = ', rnd(Tspill), 'deg K \n')

# Constants:..
c = 299792458      # EM radiation velocity m/s
pi = 3.14159      # Value of pi

b = 2*pi*f/c      # Lossless wave function
lam = c/f         # Signal wavelength (m)
zp = zl + zc      # Mismatch junction impedance sum
zm = zl - zc      # Mismatch junction impedance difference

l = np.linspace(0, lam/2, N)  # length l -axis range (m)

#transmission line calculation definitions
def exl(l):
    return np.exp(1j*(l*b) )    # complex exponential definition
def vl(l):
    return exl(l)*zp/2 + exl(-l)*zm/2    # line voltage function definition
def il(l):
    return (exl(l)*zp/2 - exl(-l)*zm/2)/zc # line current function definition
def Zl(l):
    return vl(l)/il(l)          # Line impedance
def Il(l):
    return Zl(l)/((zs+Zl(l))*vl(l))    # Load current

Pav = 1/4/np.real(zs)    # Available Power with zero reactance

# Next definitions compute available power with reactive source and load
def pa1(l):
    return (abs(np.real(zs) + np.imag(Zl(l) + zs)*1j))
def pa2(l):
    return ((np.real(zs) + abs(np.real(zs) + np.imag(Zl(l) + zs)*1j))**2 + (np.imag(Zl(l) + zs))**2)
def Pavx(l):
    # Returns available power
    return (pa1(l)/pa2(l))
def Prl(l):
    #LNA load power dissipated
    return ((abs(Il(l)))**2)*np.real(zl)

#Figure of Merit SNR equivalent
def fom(l):
    #SNR expected with antenna/LNA reactance
    return ((Prl(l)*A/Pav)/((290*(1-(Prl(l)*A/Pavx(l)))+Tlna + (Tsky+Tspill)*(Prl(l)*A/Pav))))
def fomm(l):
    # max SNR with no reactance
    return (A/((290*(1-A)+Tlna+(Tsky+Tspill)*A)) # best SNR no mismatch loss
fomx = max(fom(l)/fomm(l))    # max and min FoM
fomn = min(fom(l)/fomm(l))
def Arlx(l):
    # definition computes the complex mismatch + loss
    return (290*(1-(Prl(l)/Pavx(l))))

# plotting 3 2D plots
plt.figure(figsize =(14, 5))
sub1 = plt.subplot(1, 3, 1)
sub2 = plt.subplot(1, 3, 2)
sub3 = plt.subplot(1, 3, 3)

# The plots
# as a function of the line length between the antenna and LNA
# red - the available power compared to the no reactance case

```

```

# blue - resistive mismatches attenuation (noise) factor
# green - the product of the above = normal return loss factor
sub1.plot(l/lam, Pavx(l)*A/Pav, color='red')
sub1.plot(l/lam, Prl(l)*A/Pavx(l), color='blue')
sub1.plot(l/lam, Prl(l)*A/Pav, color='green')
sub2.plot(l/lam, 290*(1-(Prl(l)*A*Tslos/Pavx(l)))+Tlna, color='green')
sub2.plot(l/lam, 290*(1-(Prl(l)/Pavx(l))), color='blue')
sub3.plot(l/lam, (fom(l)/fomm(l)), color='magenta')

# Output data table
print ('Len/Lambda', ' ', 'Mism: Temp:', ' ', 'Avail: Power', ' ', 'Return: Loss', ' ', 'FoM' )
for ss in np.arange(N):
    if (fom(ss*lam/N/2)/fomm(ss*lam/N/2)) > 0*(fomx-(fomx - fomm)/2):
        print (rnd(ss*lam/N), ' ', rnd(Arlx((ss*lam/N/2))), ' ', rnd(Pavx((ss*lam/N/2))*A/Pav), ' ',
rnd(Prl((ss*lam/N/2))*A/Pav), ' ', rnd(fom((ss*lam/N/2))/fomm((ss*lam/N/2))) )

# naming the axes:...
sub1.set_title('Available Power (red), Resistive loss (blue),\n Signal loss (green)')
sub1.set_xlabel('TL Wavelength Fraction')
sub1.set_ylabel('Loss Factor')
sub2.set_title('Mismatch Loss(blue); Total Loss(green)')
sub2.set_xlabel('TL Wavelength Fraction')
sub2.set_ylabel('Degrees Kelvin')
sub3.set_ylim(0, 1)
sub3.set_title('SNR Figure of Merit')
sub3.set_xlabel('TL Wavelength Fraction')
sub3.set_ylabel('FoM')
plt.savefig('Graphs.png') # graphical plots
plt.show()

```

PWE November 2023



Peter East, pe@y1pwe.co.uk is retired from a Defense Electronics career in radar and electronic warfare system design. He has authored a book on Microwave System Design Tools, is a member of the British Astronomical Association since the early '70s and joined SARA in 2013. He has had a lifelong interest in radio astronomy; presently active in amateur detection of pulsars using SDRs, and researching low SNR pulsar recognition and analysis. He has recently written two other books, 'Galactic Hydrogen and Pulsars - an Amateurs Radio Astronomy' and 'An Amateurs Radio Astronomy - Small Aperture Pulsar Detection', both describing his work in Radio Astronomy. He maintains an active RA website at <http://www.y1pwe.co.uk/RAProgs/>