EA467 Transmission Lines in Space Systems: (rev b) Fall 2008

This lab introduces students to many of the practical aspects of transmission lines in spacecraft design. And a practical section on space materials in Antenna construction.

Grouping: There are 5 areas arranged as 2 setups of ABC, 2 setups of D, 2 of E, 1 of F and 1 setup of G.

Introduction: Transmission lines connect not only antennas to transmitters and receivers, but also modules and subsystems. Conductors about 1/10 wavelength or longer will have a significant reactive impedance that is a function of frequency, and this impedance must be addressed in all aspects of system design. These conductors are called transmission lines. Some common terms:

Standing Wave Ratio (SWR) - Mismatched lines loads or sources result in reflections and this causes standing waves,. The peaks of voltage and current in these standing waves cause greater losses than in a matched line. The SWR is a good quantitative measure of the amount of mismatch in a transmission line.

Impedance - Lines have a characteristic impedance (Zo). When the line is terminated on both ends by impedances that match this Zo, then maximum power transfer takes place and SWR is minimum. Transmission lines come in a few typical standard impedances, 50, 75 and 300 Ohms for example. Typical small lines for 50 ohms are RG-58 and for 75 ohms are RG-59. 300 ohm lines are balanced lines and are called “twinlead”.

Loads - The impedance of any device connected to a transmission line can be described by the real and reactive components of its impedance, R + jX in Ohms. Designers want loads to present only a real R resistance and matched so that maximum power is transferred and minimum power is reflected.

Loss - All lines have loss, and so the objective of system design is to minimize the effects of those losses. Low loss lines are expensive and usually big. Lines are typically kept as short as practical to minimize loss.

Length - A matched line can be any length and remain matched. But a non-matched line will have standing waves that will transform the impedances at the ends anywhere on the complex plane between a short and an open circuit depending only on variations in length. For example, an Open line will appear as a short ¼ wave down the line. A shorted line will appear as an open, ¼ wave away. This transformation of impedance dependent on length can be used to advantage for tuning and matching lines.

Matching - The ability of line length to change the impedance based on wavelength can be used to transform complex impedances at one end of a line to a more desirable impedance at the other. This is why transmission line length in some designs can be very significant. Matching can also use discrete L and C elements too.

Bandwidth: It is these variations in impedance with frequency and length that cause most RF systems then to only work to design specification over a specific range of frequencies. This range of frequencies is called the bandwidth of the system and is often defined as the frequency limits where SWR is below 2.0 or better, 1.5.

Velocity Factor – Radio waves at the speed of light are slowed by the dielectric constant of the insulating material in a transmission line. Typical velocity factors are 66%, 81% and 89%. This factor shortens the effective length of the line. For example, a ¼ wave at 150 Mhz is 12” in coax instead of 18” in air.

Connectors – There are a few common RF connectors you should recognize. BNC are the twist-lock connectors typically seen on small coax in labs. SMA are smaller, usually brass colored and screw-on usually used in space systems. Larger cables or higher powers use type “N” connectors (on our wattmeter and Signal Generators). The 70 year old PL-259 as used on CB sets and some consumer radios are often called UHF connectors though they are rarely used above VHF because the fat center pin makes a bump in the impedance of the line.

INSTRUMENTATION – SWR Bridge and Antenna Analyzer:

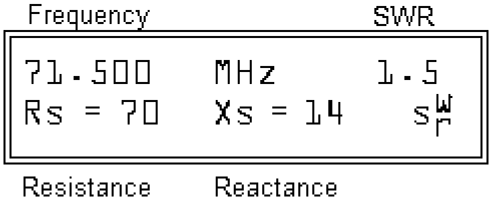
To obtain properly matched transmission lines and minimize the effects of mismatches on system performance, an SWR bridge or directional Wattmeter is used. The directional Wattmeter above left has a reversible sensor so that the forward power and reflected power can be independently measured and the SWR computed using the relationship below left. The dual needle meter in the center measures both forward and reflected power at the same time and the intersection of the needles shows the SWR. These devices are sometimes called "bridges" because they measure the difference between a known impedance (50 ohms for example) and the reflection coefficient of an unknown load.

$$SWR = \frac{1+\left(P_{ref}/P_{fwd}\right)^{1/2}}{1-\left(P_{ref}/P_{fwd}\right)^{1/2}}$$

$$\Gamma = \left|\frac{V_r}{V_i}\right| = \left|\frac{Z_L - Z_0}{Z_L + Z_0}\right|$$

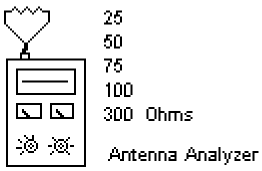
Reflection Coeficient

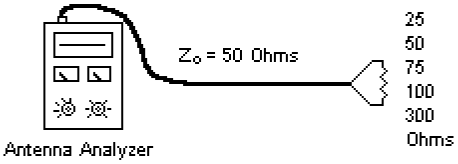
$$\text{VSWR} = \frac{1+\Gamma}{1-\Gamma}$$

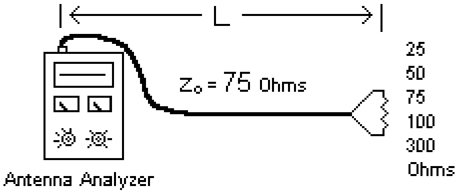


The Reflection Coefficient which is also related to SWR can be computed from the differences in the impedance of the lines as shown in the middle equation above. It can then be used to compute the Voltage Standing Wave Radio. The second instrument, on the right above, is called an Antenna Analyzer. Internally it has an oscillator and SWR bridge for comparing the impedance of an attached line or load. The LCD display as sketched above shows the Frequency of operation, the SWR magnitude and the Real and Reactive components of the impedance. Two analog meters also show the SWR and real impedance for easy tuning. With no action, it goes to sleep to save battery power. Press GATE to awaken it.

Part A. Characteristic Impedance: In this experiment you will measure the effect on SWR of several different lines and different load impedances as shown below.







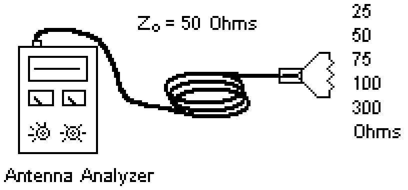
1. Set the Antenna Analyzer to "Impedance R and X" by pressing the MODE key and tune to about 55 MHz. Then measure the SWR and Impedance without any transmission line of an open circuit. Next connect a 24, 51, 75, 110 and 300 ohm resistor (or load) connected directly to the analyzer using a short double-female adaptor. During each measurement, TUNE from about 27 to 70 MHz

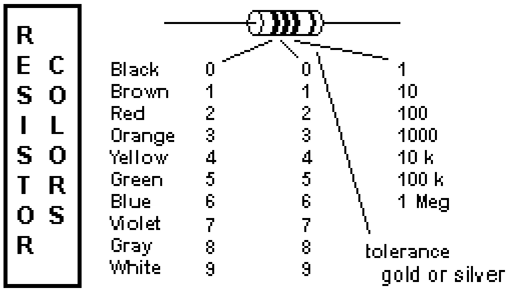
and notice any effects. With no length of coax, these first measurements should show no frequency effect; but the effects will be greater in later steps. Which load gives the closest real impedance reading to its actual value and which one remains the most constant with frequency.

2. Next use a 4 foot 50 Ohm line (RG-58). Measure the length and compute the frequency where this line is ¼ wave in coax with a velocity factor of 66%. Repeat the six measurements with the different loads or part 1. Again, tune from 27 to 70 MHz and note any maxima or minima and if they occur, take your readings at that point. Otherwise, record the data at about 55 MHz.

3. Repeat part 2 on a 4 foot section of 75 ohm line (RG-59 type). Note which value has the closest to 50 ohms when frequency is adjusted for optimum? What is that frequency.

4. Repeat the part 2 measurements on a very long 50 Ohm line (has some loss). You will notice the SWR appears to be better (lower), not because the SWR on the line is actually lower, but because the losses in the coax attenuate the reflection from the far end and this makes the SWR “appear” to be lower when in fact, it is not. This is a common error made by many newcomers to the field.

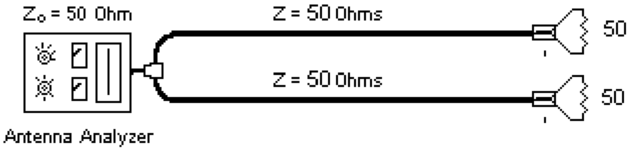




5. Comment on lessons learned with respect to best impedance match as observed with the lowest SWR in the various combinations tested.

Part B. Combining Loads or Splitting Power: Very often in electronics, power on a transmission line has to be shared or combined among two or more loads. At low frequencies, where the length of the wire is very small with respect to wavelength, things can be connected in parallel with simple wires at a point. But at RF frequencies, any attempt to parallel loads must take into account the impedance of the line and its length and the transforming effects of mismatched loads.

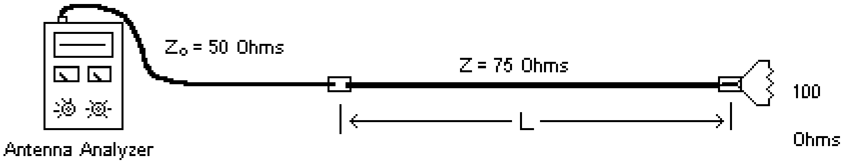
When you combine two 50 ohm loads with negligible line length, you get a 25 Ohm effective load and this has an appreciable mismatch to 50 ohm cable. Confirm your higher readings for the 25 ohm loads compared to the 50 ohm load you observed in Part A-1 and 2.



1. To demonstrate this, use a “T” connector to connect two 4 foot 50 ohm lines with 50 ohm loads together onto your 50 ohm antenna analyzer as shown below. This also causes a combined 25 ohm parallel combination at the “T” and you should see about the same SWR you measured when you used only a 25 Ohm resistor in part A. Vary the frequency and note any changes in SWR. It should remain poor across all frequencies because the mismatch at the “T” remains 25 Ohms no matter how long the length of the lines. *Remember this for the next part; you cannot simply connect matched RF lines with a “T” connector.*

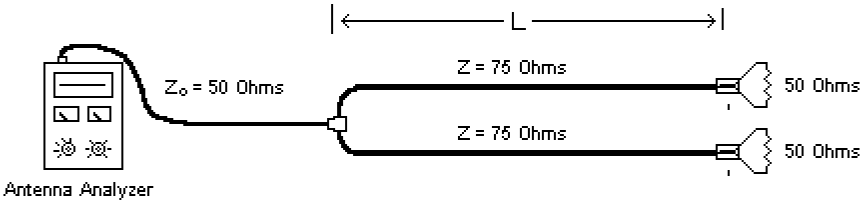
Part C. Quarter Wave Transformers: The length of a section of transmission line can move the complex impedance around on the complex plane. A quarter wave section of line will perform a 90 degree transformation of the impedance in the complex plane. This ¼ wave line can transform a short to an open, and an open to a short or *any other* ***real*** *impedance to a different* ***real*** *impedance according to the following relationship:* $Zin * Zout = Zo^2$

1. If you have a 100 ohm antenna and you want to transform it to your 50 ohm cables and transmitter, then a length of ¼ wave 75 ohm line as shown below will do it according to the above relationship. In fact, this is a portion of what you measured in Part A3. Verify that with 100 ohms at the end of the 75 ohm line, that you did get a low SWR reading in part A3. If not, re-do the test.



2. A great application of this impedance transformation is when combining two 50 ohm antennas for increased gain (+3dB) as was attempted in part B. In that case the SWR indicated a mismatch, because the parallel loads combined as 25 ohms and upset the 50 ohm system.

But you can build a matching system using ¼ wave lines. First connect each 50 ohm load to ¼ wave of 75 ohm line as shown below. This transforms the 50 ohms to 100 ohms at the near end of the cable by the above equation. Now connect these two effective 100 ohms in parallel using the simple "T" connector as shown below and the resulting impedance according to the above equation is near 50 ohms and a great match for a 50 ohm system (but only at that frequency where the lines are exactly ¼ wavelength.)

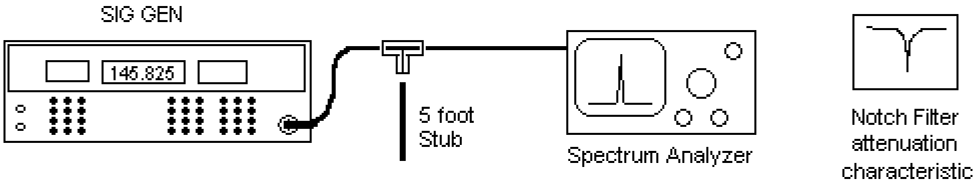


Use the TUNE knob to find the minimum SWR frequency which should occur where the 75 ohm lines are ¼ wave long. Remember from part A2 to include the 66% velocity factor in your line length calculations. This should be a good match and demonstrates that the two loads are now in parallel and matched. Indicate the useable *bandwidth* of this system by the range of frequencies over which the SWR remains below 2.0.

In these examples, you have built what is often called a "phasing line" to match the 100 ohm load to a 50 ohm system or a "phasing harness" to allow you to parallel two 50 ohm loads together and still maintain a match. Notice that the length of the coax lines must be ¼ wavelength at the frequency of operation for this match to occur. *A phasing harness is often used on spacecraft to split or combine power from two or more antennas or loads. Sometimes this function is packaged in a small box and called either a "splitter" or "combiner".*

Post-Lab work: Using the diagram above, sketch how you might design a phasing harness using ¼ wave phasing lines to combine Four 50 ohm antennas to a single 50 ohm line.

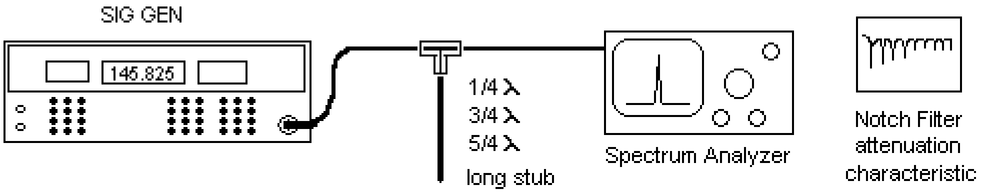
Part D: Notch Filters: (2 Setups). You can use a similar ¼ wave transformation effect as a notch filter. Since a ¼ wave line that is open on one end will reflect a short to the other, you can connect this "stub" with a "T" connector and at one frequency where the line is exactly ¼ wave, the signals on the line will be shorted. To demonstrate this, connect a signal generator and spectrum analyzer as shown below. The spectrum analyzer sweeps across a range of frequencies to show the amplitude against frequency. Ignore the apparent "signal" at "zero" frequency and the mirror image of frequency below that.



Connect the signal generator to the spectrum analyzer without any stub connected to the "T" and set both for a 0 dBm level centered at about 40 MHz. Set SPAN WIDTH to 5 MHz/div. You should be able to tune the signal generator from about 20 to 60 MHz and see very little change in amplitude of the signal delivered to the spectrum analyzer. Use the coarse/fine and up/dn buttons for tuning. Record this level for comparisons in the following steps.

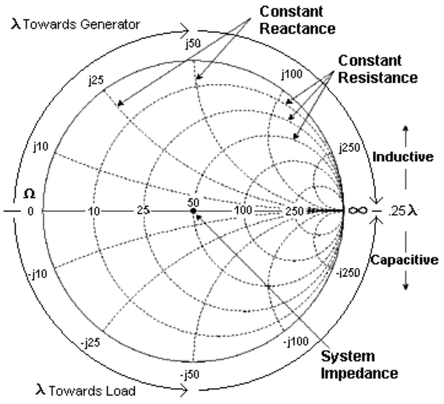
1. Now "T" in a 4 foot piece of line (green tape) as shown above. The Zo of this stub does not matter. Why? Compute the frequency for which it is ¼ wave and tune to that frequency. Remember to include the shortening effect of the dielectric constant of the line (usually 66%). Tune around that frequency to find the frequency that gives the maximum attenuation (minimum signal). Use the coarse/fine and up/dn buttons for tuning in 1 and 0.1 MHz steps as needed. Observe the attenuation of this simple "1/4 wave notch filter" in dB (difference with and without the stub connected)?

What does this tell you about leaving unterminated lines in any test configuration?



2. Any line that is an odd multiple of ¼ wave will produce a similar notch at 3, 5, etc times higher frequencies (Why?). Tune the sig-gen to higher frequencies and follow with the spectrum analyzer and you should find multiple attenuation notches. However, at higher and higher frequencies, the stub line appears "longer and longer" and so will have more and more loss in the stub. This reduces the effectiveness of the reflected "short" and so the attenuation is not as great. But this makes a nice "comb" filter for taking out all the harmonics of a particular set of frequencies. What is the depth of the notch at the ¾ and 5/4 wave frequencies?

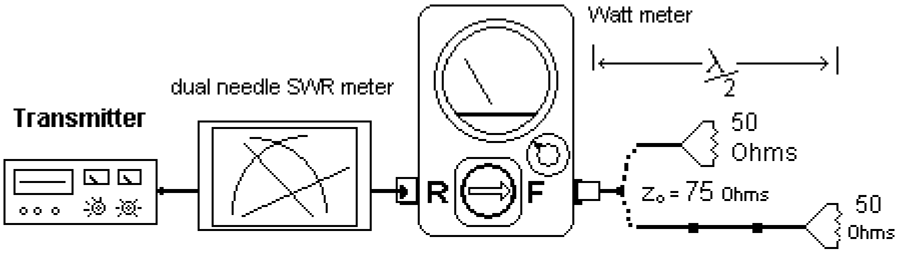
3. Proceed into the R121 Lab and observe the same ¼ wave stub filter as it appears on our new RF Network Analyzer. You can see the complex impedance plotted on a Smith Chart as well as a swept-frequency plot. Rotate the Marker knob to find the frequencies of maximum attenuation.



Part E: ½ Wave Lines:

You can back-to-back two ¼ wave lines so the Zout of one is the Zin of the other. Using the equation in part C twice, the first complex transformation will be reversed by the second one resulting in an exact duplication of the original impedance every ½ wave down a line. This means that a ½ wave line will virtually “disappear” as far as it’s characteristic impedance is concerned. You can use this special feature to get an impedance from point A to point B inside a system without worrying about matching the line impedance…. Just make the line exactly ½ wavelength long.

For this exercise, you will use a 5 Watt CB transmitter at 27 MHz and a common Navy Bird Wattmeter and a dual-needle Meter to measure SWR. The Wattmeter measures forward and reflected power that you then have to convert to SWR using the equation given on page 2. But the dual-needle watt meter measures forward and reflected power simultaneously and has a grid (in red) for observing the actual SWR that results from the two readings.

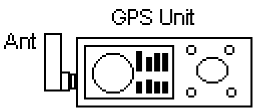


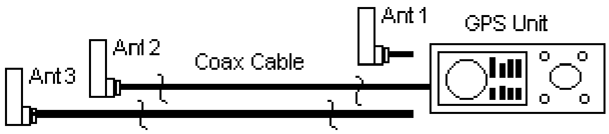
1. Place the short 75 ohm coax with 50 ohm resistor load on the wattmeter. Measure the SWR by reading the 27 MHz TX power (Channel 1) in the forward and reverse direction (rotate the watt-meter sensor with the arrow). Compute the SWR using the equation on page 2. Compare your measured SWR to that in Part A3 for a 50 ohm load on a 75 ohm mismatched line. Compare your value to that observed on the dual needle SWR meter also.

2. Now add one, then two additional 4’ long 75 ohm blue coax lines and again measure the forward and reflected power and compute the SWR. During transmit with very low reflected power, hold the transmitter on for a full 5 seconds to get a reading). Measure the total length of the 3 sections and compute the ½ wave frequency. Remember to divide your measurement by the 66% velocity factor in coax to calculate its effective length in free space . Is this length close to ½ wavelength at 27.0 MHz (Channel 1)? Make this last SWR measurement again on channel 40 (27.4 MHz) to see any difference across the 40 channel CB band.

Post Lab: Comment on your observations, measurements and the advantages and practical use of ½ wave lines.

<u>Part F. Cable Loss (GPS):</u> To get higher in frequency where cable loss is more apparent, we will use a GPS receiver for this experiment out on the Plaza. Long cables waste power in transmit systems and weaken signals in receive systems. This experiment demonstrates the loss of signal and Signal-to-Noise-Ratio (SNR) using two lengths of coaxial cable at the GPS operating frequency of 1575 MHz. At this high frequency, even short cables have measurable loss.

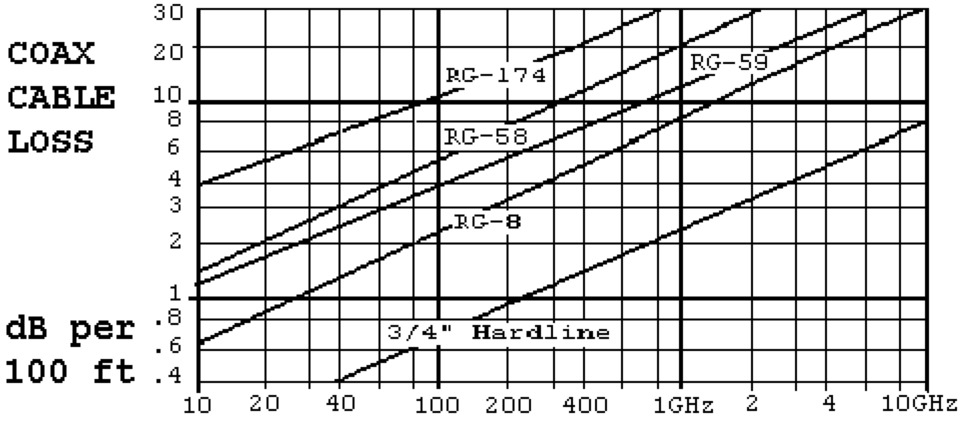




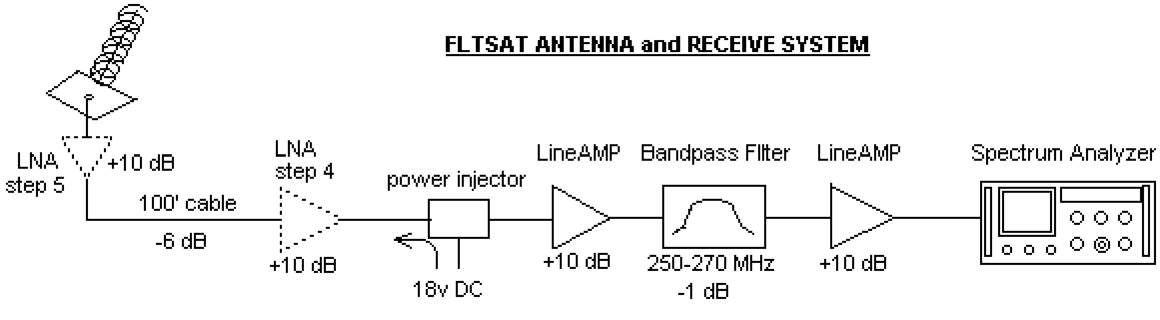
Lab Period: (Plaza) : Set the GPS to the satellite signal strength page:

1. Connect the antenna directly to the GPS and hold the unit clear of all objects. Allow a minute for the receiver to obtain a fix. Record the relative signal strength and note the positions of the satellites. Assume the top line on the display is the 0 dB reference and each line is -3 dB from the line above.
2. Now move the antenna to the end of the 18’ length of small RG-58 cable. Allow a minute for the receiver to resume lock. Record the satellite relative signal strengths.
3. Next move the antenna to the end of the 16’ length of low-loss RG-8 cable. Allow a minute for the receiver to obtain lock. Record the satellite relative signal strengths.

Post-Lab: Compare the measured signal losses to the expected losses and to each other. Discuss the importance of cable selection. (Do satellites lower on the horizon have slightly lower signal strengths. See the chart of coax cable loss per 100 feet below. How does your data compare?



Part G. Cable Loss and Low Noise Amplifiers (LNAs): In this section you will use a Navy UFO satellite as a signal source to study the effects of cable loss on the signal-to-noise ratio that determines receive side performance. You will make several signal and noise measurements with and without the LNA at each end of the cable. For consistency, use the 6th transponder from the left of the several UFO channels. Notice that the LNA is a short barrel about the size of your thumb mounted in-line at the antenna end of the coax.



Lab Period: (Plaza/Lobby)

1. With nothing connected to the Spectrum Analyzer, tune to 254 MHz with a bandwidth of 300 kHz and scanwidth of 2 MHz per division. Set the Log Reference Level to –50 dBm and Linear Sensitivity to 0 dBm. Determine the noise strength in dBm of the Analyzer noise floor (the RMS average of the noise peaks).
2. Now connect the cable to the Spectrum Analyzer with the LNA connected out at the antenna, point to the CONUS UFO (220° AZ and 45° EL) Notice how the 10 signal channels are well above the noise floor (at least

16 dB or more). Observe the signal power level compared to the noise power level and thus, (difference) the Signal-to-Noise ratio (SNR). The noise level is higher now due to the noise of the amps between the antenna and spectrum analyzer.

3. Now move the LNA from the antenna into the lobby operating position. Connect it in front of the power injector and two line amps where the cable connectors are marked with yellow tape. Observe the noise level, signal level, and SNR. The difference here is that the cable loss is now in front of the LNA instead of after it. Comment on the lesson learned here.
4. Now remove the LNA and reconnect the cables. Observe the noise level, signal level and SNR now without the benefit of the LNA. Comment on this observation.
5. Now eliminate the gain of the two additional line amps by connecting the antenna directly to the spectrum analyzer. Do this by disconnecting the short cable to the spectrum analyzer at the output of the last line amp and connecting it to the end of the long coax out to the antenna (without the LNA). Now observe the noise level, the signal (if any) and the SNR. Probably you cannot see the signal at all because you have lost over 30 dB of amplifier gain that was being used to get the signal above the noise floor of the spectrum analyzer and the cable loss. Comment on your observations.
6. Restore the system to normal, re-connect the two 20 dB line amps and move the LNA back out to the antenna for the next group.

Transmission lines Laboratory Report: This is a simple lab. You have made lots of observations from which you can support many of the theories about transmission lines and their practical application. In each element of the lab you were told what values to collect and what results to observe. With this background, submit a team report as follows:

- ✓ For each part of the lab as appropriate, include a drawing of the setup, and a table of the observations, including comments on any of the values that may have appeared to have a sensitivity to frequency or other variables.
- ✓ Based on your observations, write conclusions for each part relative to the principal or function that was involved. Answer all questions and comment on all salient points observed.
- ✓ Include an overall introductory section and conclusions section. Your report will be graded on how well it stands alone as a treatise on the practical aspects of transmission lines for connecting the various transmitters, receivers, antennas and other systems on spacecraft as supported by your experiments.