Low Cost, Compact Microwave Reflectometer for Non-Destructive Testing

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Project Summary:

A low-cost reflectometer for non-destructive is an instrument capable of measuring the phase and magnitude of the reflection coefficient of an unknown load. When used for non-destructive testing, an open-ended coaxial cable is inserted in a liquid or pressed against a material. Through additional analysis, the reflection coefficient from the material can be related to physical properties of the material. The reflectometer consists of a six-port passive microwave circuit integrated with a PC workstation. The PC workstation samples four output voltages and calculates the phase and magnitude of the reflection coefficient using a specified algorithm.

Detailed Description:

The system consists of a RF Block and a Software Block. The RF Block is designated by a dashed boundary in figure 1. The system is controlled by software installed on the PC. The RF Block will be discussed followed by the software flow charts.

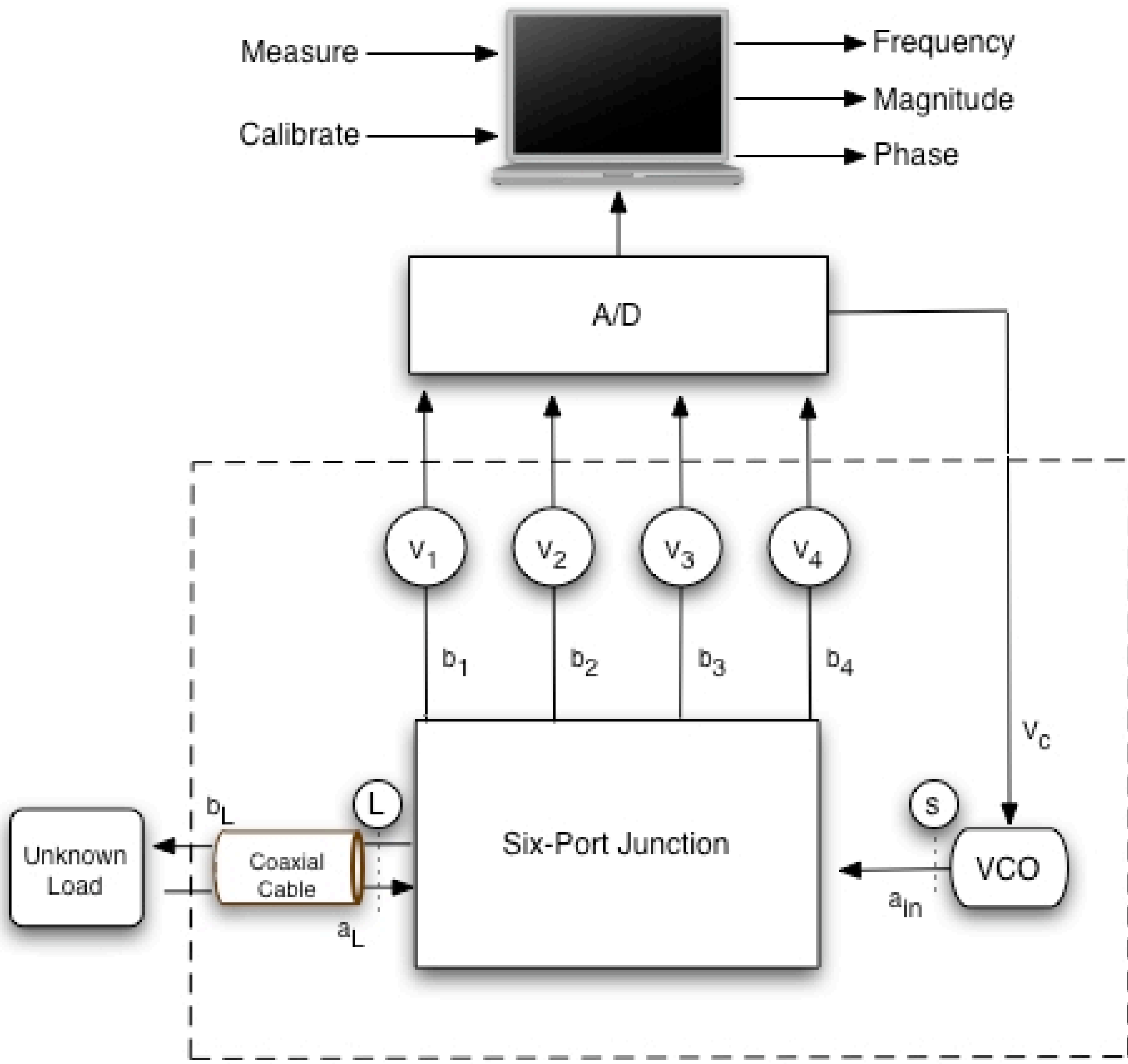

Figure 1: System Block Diagram

The radio frequency (RF) component consists of the six-port junction, voltage controlled oscillator (VCO), four microwave detectors, and a coaxial cable. The six-port junction analyzer is a passive micro-strip circuit, which can be implemented with quadrature hybrids. The VCO produces an RF reference signal and is controlled by a DC voltage, V_c. The signal from the VCO (a_{in}) enters the 6-port junction at port-s and, in general, is split among all the other ports. At port L, two signals exist simultaneously. One exits the port (b_L) and is the incident wave on the unknown load. The other enters the port (a_L) and is the reflected wave from the unknown load. The ratio of the reflected wave to the incident wave (relative to the load) is the reflection coefficient. Using a scattering matrix model for the 6-port junction, it can be shown that the signals exiting ports 1 through 4 contain information concerning (a_L) and (b_L). The detectors V_1, V_2 , V_3 and V_4 on the ports convert the RF signal to low frequency voltages proportional to the RF power detected. These signals are sampled and stored in the PC where a complex algorithm computes the reflection coefficient of the unknown load.

There are two modes of operation: measurement and calibration. The measurement mode will allow the user to determine the reflection coefficient of the unknown load at different specified frequencies. The calibration mode will allow the user to determine system parameters by the use of known loads. These parameters are utilized in the algorithm to find the reflection coefficient of the unknown load.

The flowchart for the calibration mode of the six-port network analyzer is shown in figure 2. The user first selects a frequency at which the system will measure the reflection coefficient. Once the frequency has been entered, the program prompts the user to connect a specific load at port-L. The program then samples the voltage readings (V_1, V_2 ,V_3 and V_4) and stores the binary values into memory. The program notifies the user by a prompt if it is processing the data. This is repeated for each specific calibration load as the program prompts the user for each load. An algorithm then uses the voltage readings to calculate the system parameters needed for measurement. Once this is finished, the user may then proceed to the measurement mode and begin taking measurements of an unknown load. Though it is possible to calibrate and measure over a band of frequencies, the current system will require recalibration and measurement for each different frequency.

Once the calibration has been completed, the user will then proceed to the measurement mode of the software, which is shown in figure 3. The user is notified to connect the unknown load at port L. The system will then proceed to take measurements of the voltage levels (V_1, V_2, V_3 and V_4) and store binary values into memory. An algorithm then processes the values stored in memory in correlation with the calibration results. The user is prompted with results showing the magnitude and phase of the load as well as the frequency of the measurement.

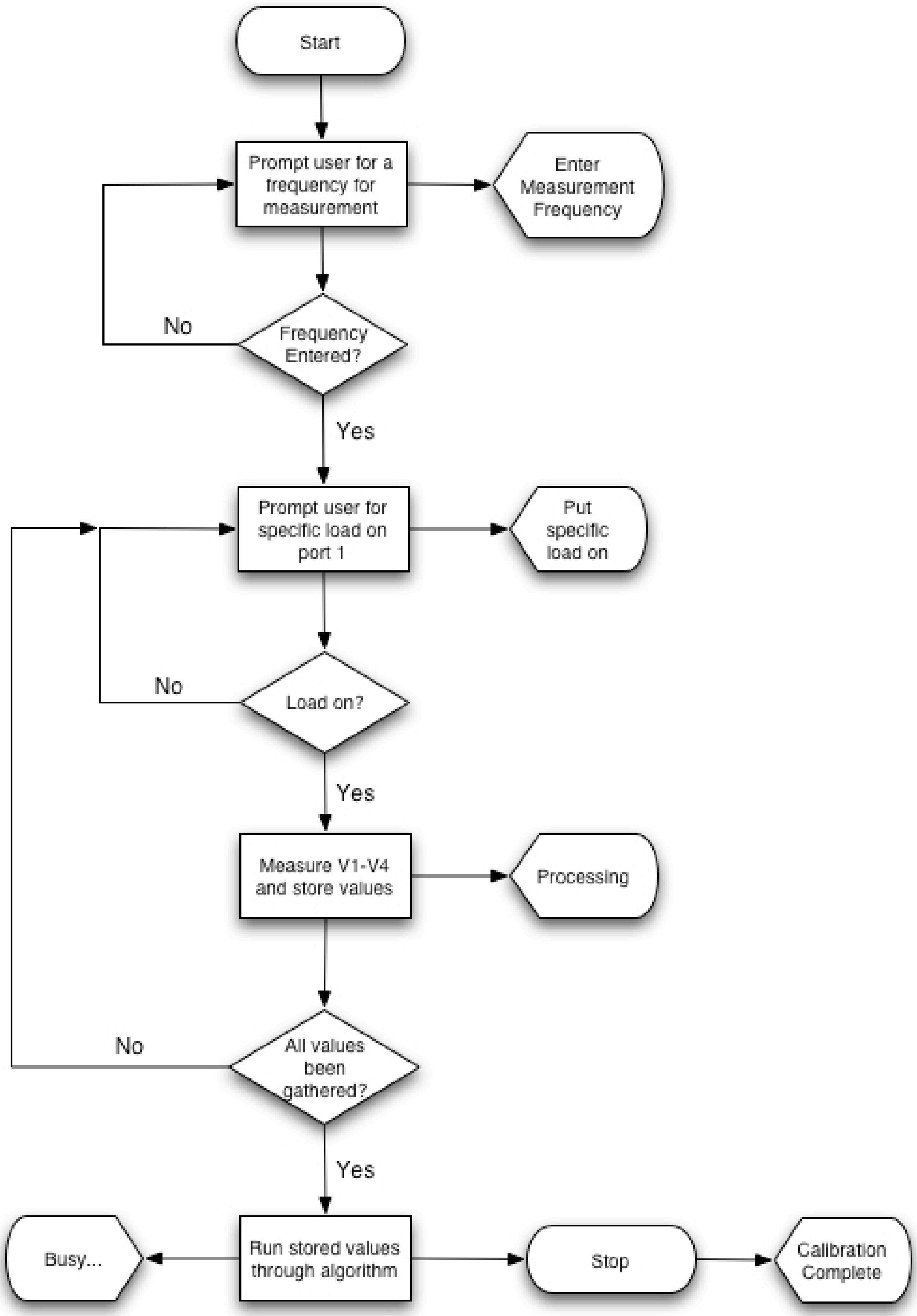

Figure 2: Calibration Flowchart

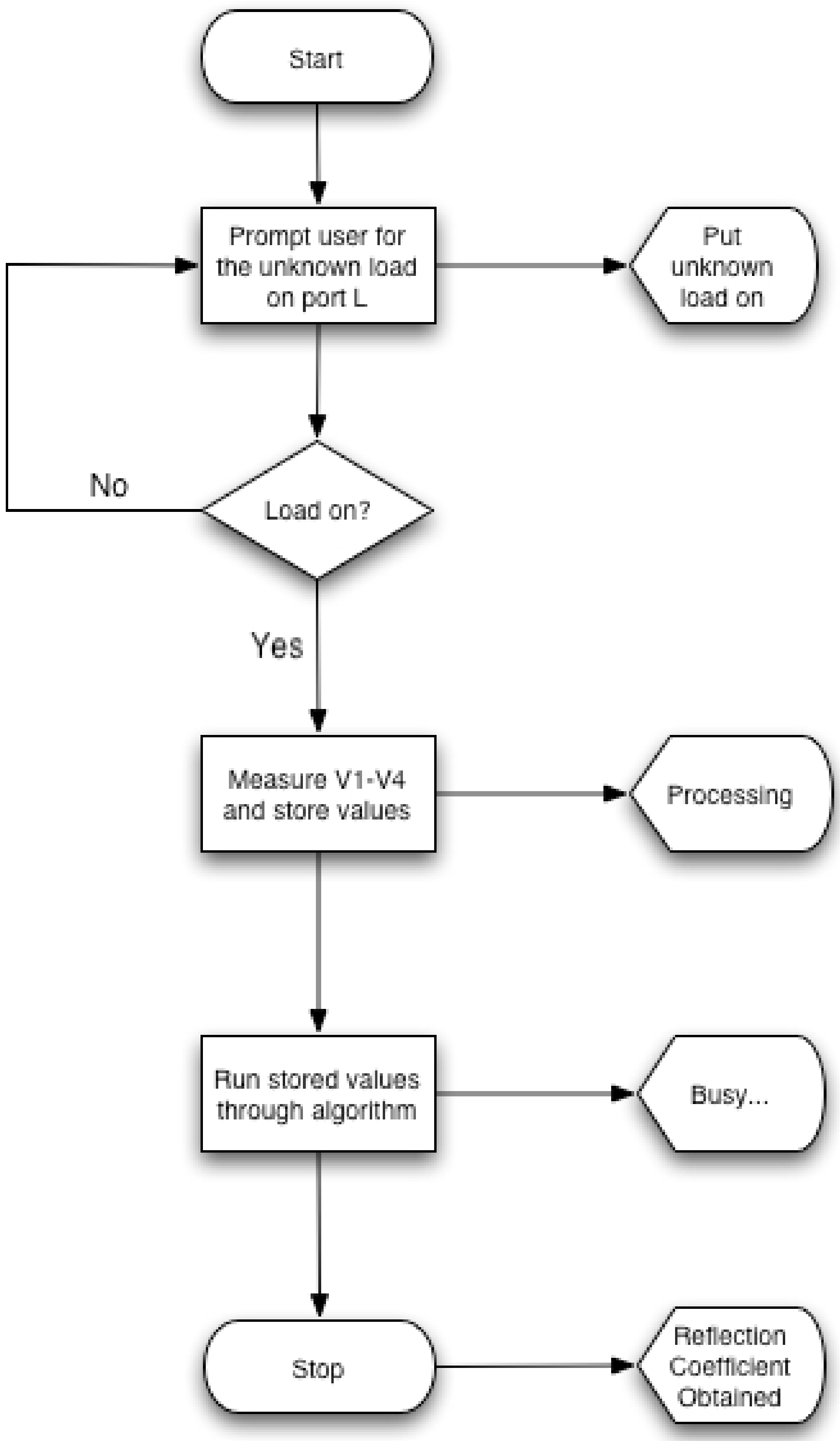

Figure 3: Measurement Flow Chart

Inputs/Outputs:

The system consists of an RF subsystem and computer software subsystem as shown in Figure 1. The RF block input consists of an RF source, which generates a signal that is routed by a six port passive circuit to five other ports. An unknown load is attached to one of these ports. A signal exits this port and is incident on the unknown load. Due to the mismatch, a reflected wave is generated and propagates back into the RF subsystem. The incident and reflected waves exit simultaneously in a coaxial cable. At four other ports of the passive circuit, the various signals combine delivering power to detectors, which result in voltages V_1, V_2, V_3, and V_4. The frequency control signal sets the frequency of operation. Table 1 describes the inputs and outputs to the RF block.

The software inputs consist of the following: reset, increment frequency, decrement frequency, measure, measure mode, and calibrate mode. Connected internally between the RF block and the computer software block are four voltages V_1, V_2, V_3, and V_4. The software will sample these four voltages, which will be used in a series of computations to find the reflection coefficient of the unknown load. Another internal connection between the subsystems is a frequency control signal and this will determine the frequency at which the system will operate. The outputs are the magnitude, phase, and frequency of the unknown load. Table 2 describes the inputs and outputs to the computer software block.

Inputs	Outputs	Operations
Reflected Signal		Created from the incident signal which is used to calculate the Reflection Coefficient.
Frequency Control		Sets the frequency of operation.
	V_1, V_2, V_3, and V_4	Sampled voltages to calc. Reflection Coefficient.
	Incident Signal	Sent to the load.

Table 1: RF I/O and Mode of Operations

Inputs	Outputs	Operations
Reset		Initialize the entire system.
Increment Freq.		Increase frequency of the reference signal.
Decrement Freq.		Decrease frequency of the reference signal.
Request		Take measurement.
Mode1: Measure		Set the system to measure.
Mode2: Calibrate		Set the system to be calibrated.
	Magnitude	Displayed on user's workstation.
	Phase	Displayed on user's workstation.
	Frequency	Displayed on user's workstation.
	Calib. Disp.	Direct the user to calibrate the device properly.

Table 2: Software I/O and Mode of Operations

Methods:

The design team plans to build an optimal micro-strip design layout for the six-port passive junction that is within the RF subsystem. This design will allow for a small, low-cost device that will use a workstation to allow convenient measurement of the reflection coefficient of an unknown load. If an open-ended coaxial cable is used, then the reflection coefficient can be related to physical parameters of the material that is in contact with the open end of the probe. A software package will be designed that will use a computer to perform the necessary calculations. The PC will be used for convenience, speed, and capabilities of producing superior results.

Analytical Equations:

The six-port junction will probably use an optimal, passive micro-strip design with quadrature hybrids. The VCO produces an RF reference signal and is controlled by the DC voltage, V_c. The signal from the VCO (a_{in}) enters the 6-port junction at port S and, in general, is split among all the other ports. At port-L, two signals exist simultaneously. One exits the port and is the incident wave (b_L) on the unknown load. The other enters the port and is the reflected wave (a_L) from the unknown load. The ratio of the reflected wave to the incident wave (relative to the load) is the reflection coefficient. Using a scattering matrix model for the 6-port junction, it can be shown that the signals exiting ports 1 through 4 contain information concerning (a_L) and (b_L). The detectors V_1, V_2 , V_3 and V_4 on the ports convert the RF signal to low frequency voltages proportional to the RF power detected. These signals are sampled and stored in the PC where a complex algorithm computes the reflection coefficient of the unknown load.

To obtain the reflection coefficient (Γ), a relationship to measured powers must be obtained to compute the magnitude and phase of Γ. The starting point for the derivation is the matrix equation shown in equation 9-1 and assumes matched detectors on ports 3, 4, 5, and 6 ($a_3 = a_4 = a_5 = a_6 = 0$). From here on, the ports have been relabeled, port-s is referred to as port-1 and port-L is port-2. Using basic matrix multiplication it is possible to find an expression for b_1 to b_6 as given by equation 9-2. Setting $a_2 = b_2\Gamma_2$ further manipulation of the expressions for b_y (y = 1, 2, 3, 4, 5, 6) yields equation 9-3. If the terms containing s-parameters are replaced by complex coefficients, then equation 9-3 can be written as equation 9-4. The coefficients C_x and D_x (x = 3, 4, 5, 6) characterize the six-port junction in this application. In the operation, the powers at ports 3, 4, 5, and 6 are measured. These powers are given in equation 9-5. These powers are positive real quantities and contain no phase information. However, it is possible to extract magnitude and phase values from the power measurements via complex algorithms.

There are two basic analytic computations that need to be done. One step is to determine the C_x and D_x coefficients or related quantities. This will be done by placing several known loads on port-2. The final algorithm to compute C_x and D_x has yet to be determined. Once the six-port junction has been calibrated, then the unknown load is placed on port 2 and the powers P_3, P_4, P_5, and P_6 are measured. These powers can be used to find magnitude and phase of Γ_2. One approached discussed in the literature (Engen 2) forms ratios of the powers, which leads to equations for three circles in the complex Γ plane. Finding the intersection of these circles yields the value of Γ_2. This procedure is complicated by the fact that there is no exact intersection in a noisy system. An alternative technique using MATLAB will also be investigated. This approach, if possible, is new and not discussed in the literature.

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ s_{31} & s_{32} & s_{33} & s_{34} & s_{35} & s_{36} \\ s_{41} & s_{42} & s_{43} & s_{44} & s_{45} & s_{46} \\ s_{51} & s_{52} & s_{53} & s_{54} & s_{55} & s_{56} \\ s_{61} & s_{62} & s_{63} & s_{64} & s_{65} & s_{66} \end{bmatrix} \bullet \begin{bmatrix} a_s \\ \Gamma_2 b_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix} \qquad \textbf{(9-1)}$$

$$b_y = s_{y1}*a_s + s_{y2}*a_2 \qquad \textbf{(9-2)}$$

$y = 1,2,3,4,5,6$

$a_s = a_1$

$$b_x = (s_{x1}/s_{21}) \cdot b_2 + [s_{x2} - (s_{22} \cdot s_{x1})/s_{21}] \cdot a_2 \qquad \textbf{(9-3)}$$

$$b_x = D_x \bullet b_2 + C_x \bullet b_2 \Gamma_2 \qquad \textbf{(9-4)}$$

$$P_x = |b_x|^2 \qquad \textbf{(9-5)}$$

$x = (3,4,5,6)$

Standards:

There are no current standards that exist for a six-port network analyzer.

Patents:

There are a few patents that exist for a microwave reflectometer. Five patents were narrowed down that represented the project the most. These patents are shown in table 3.

	Patent #	Title
1	5,274,333	Frequency Balanced six-port reflectometer with a variable test port
2	4,808,912	Six-port reflectometer test arrangement and method
3	4,680,538	Millimeter wave vector network analyzer
4	4,521,728	Method and a six port network for use in determining complex reflection
5	4,104,583	Six-port measuring circuit

Table 3: Patent List

Equipment List:

USB A/D Converter
PC Workstation with a USB connection
Four Coaxial Detectors (Voltage Detectors)

Division & Schedule of Tasks:

		Matthew Rangen	Keith Bruno
January	21 to 27	Develop Calibration & Measuring Equations	Design 90º Hybrid
Jan/Feb	28 to 3	·	Simulate & Test 90º Hybrid
		Purchase: Detectors & USB A/D	
February	4 to 10	·	Design & Simulate 6-Port
	11 to 17	Implement Equations in MATLAB	·
	18 to 24	Test Equations	Design & Simulate Interface
Feb/March	25 to 3	Integrate MATLAB & A/D	Fabricate 6-Port
March	4 to 10	Test Programming Code	·
	11 to 17	Spring Break	
	18 to 24	·	Test 6-Port
	25 to 31	·	·
April	1 to 7	System Integration & Testing	
	8 to 14	·	
	15 to 21	Verify Operation	
	22 to 28	Final Report & Presentation Preparation	
April/May	29 to 5	Final Report due, Presentation & Final Exams	
May	6 to11	Final Exams	

Data Sheet:

Frequency of Operation	2 GHz - 10 GHz
Accuracy of Γ Measurement	TBD
Frequency Step Resolution	TBD
Power Requirement	5V
Dimensions of six-port junction	
Size	TBD
Weight	TBD
Operating System	Windows, Mac OS, Linux
Computer	USB capable, 256 Meg of Ram
Software	MATLAB

TBD = to be determined

Bibliography:

[1] J D Hunter and P I Somlo, "An Explicit Six-Port Calibration Method using Five Standards," IEEE Trans., vol MTT-33, no. 1, January, 1985, pp 69-72.

[2] G F Engen. "The six-port reflectometer: An alternative network analyzer," IEEE Trans. Microwave Theory Tech., vol MTT-25, December, 1977, pp 1075-1080.

[3] G F Engen. "An Improved Circuit for Implementing the Six-Port Technique of Microwave Measurements," IEEE Trans. vol MTT-25, no. 12, December, 1977, pp 1080-1083.

[4] Dr. Brian Huggins. Personal Interview. October till present.