Supplementary Information and Figures

SPECTRAL CHARACTERIZATION OF DIELECTRIC MATERIALS USING TERAHERTZ MEASUREMENTS SYSTEMS

By Jeffrey Seligman

1.0 Material Parameter Plots vs Sample vs Frequency

Table 14: Summary for three samples on VNA and TDS

Parameter	Sample	Mfgr value (10GHz)	VNA/PSU (325-500 GHz)	VNA/VDI (500-750GHz)	TDS (200-1.5 THz)
	R3006x25				
Er'		6.15	7.3	7.8	7.6
Er"		0.0123	0.124	0.358	0.25
Tan (d)		0.002	0.0169	0.0478	0.025
	TMM10				
Er'		9.2	10	10.63	10.9
Er"		0.0202	0.12	0.111	0.1
Tan (d)		0.0022	0.012	0.0096	0.015
	R6002				
Er'		2.94	2.92	2.97	2.93
Er"		0.00353	0.0039	0.008	0.02
Tan (d)		0.0012	0.0013	0.0028	0.008

Table 1 Summary for three samples on VNA and TDS, R3006, TMM10, and R6002

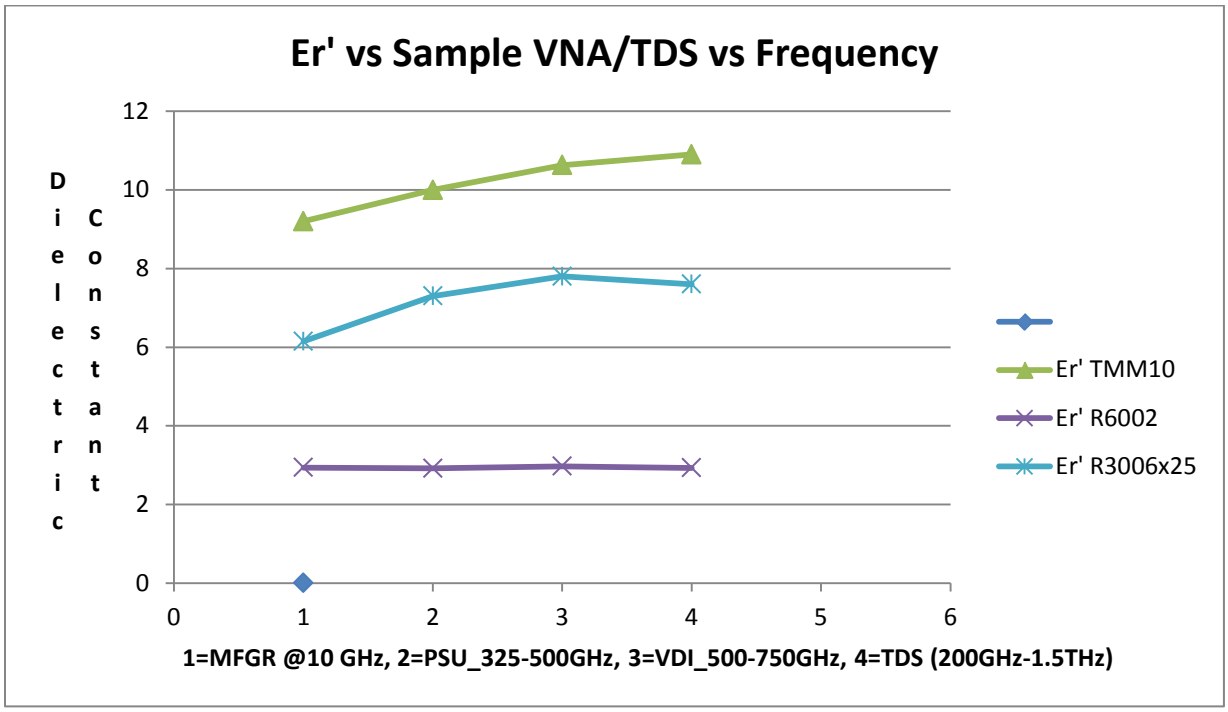


Figure 1 Dielectric Constant Er' for 3 Samples VNA/TDS vs Frequency, TMM10, R30006, R6002

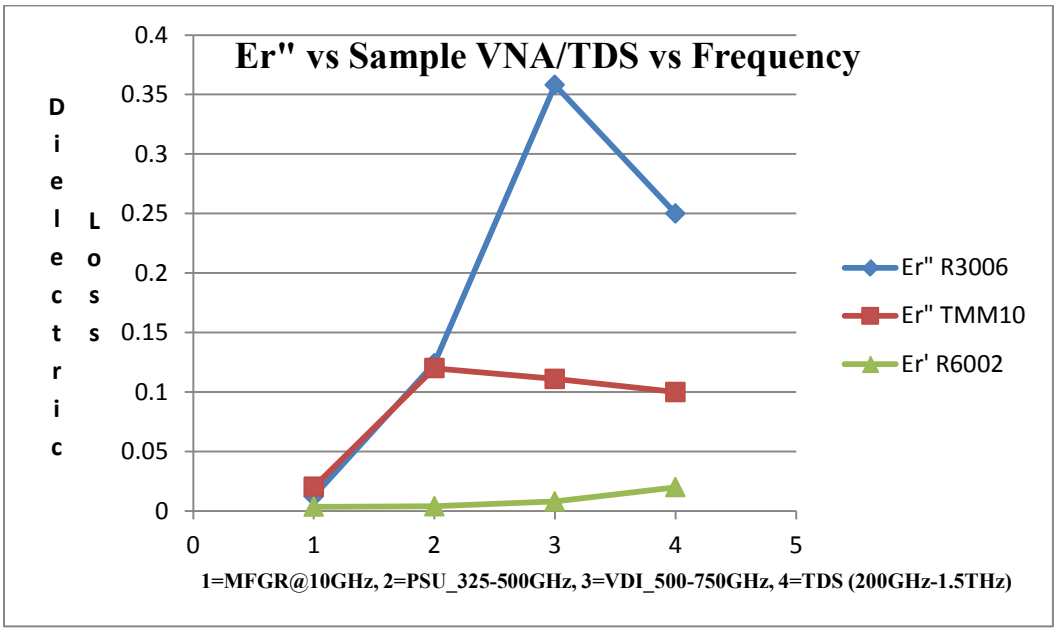


Figure 2 Dielectric Loss Er" vs Sample VNA/TDS vs Frequency

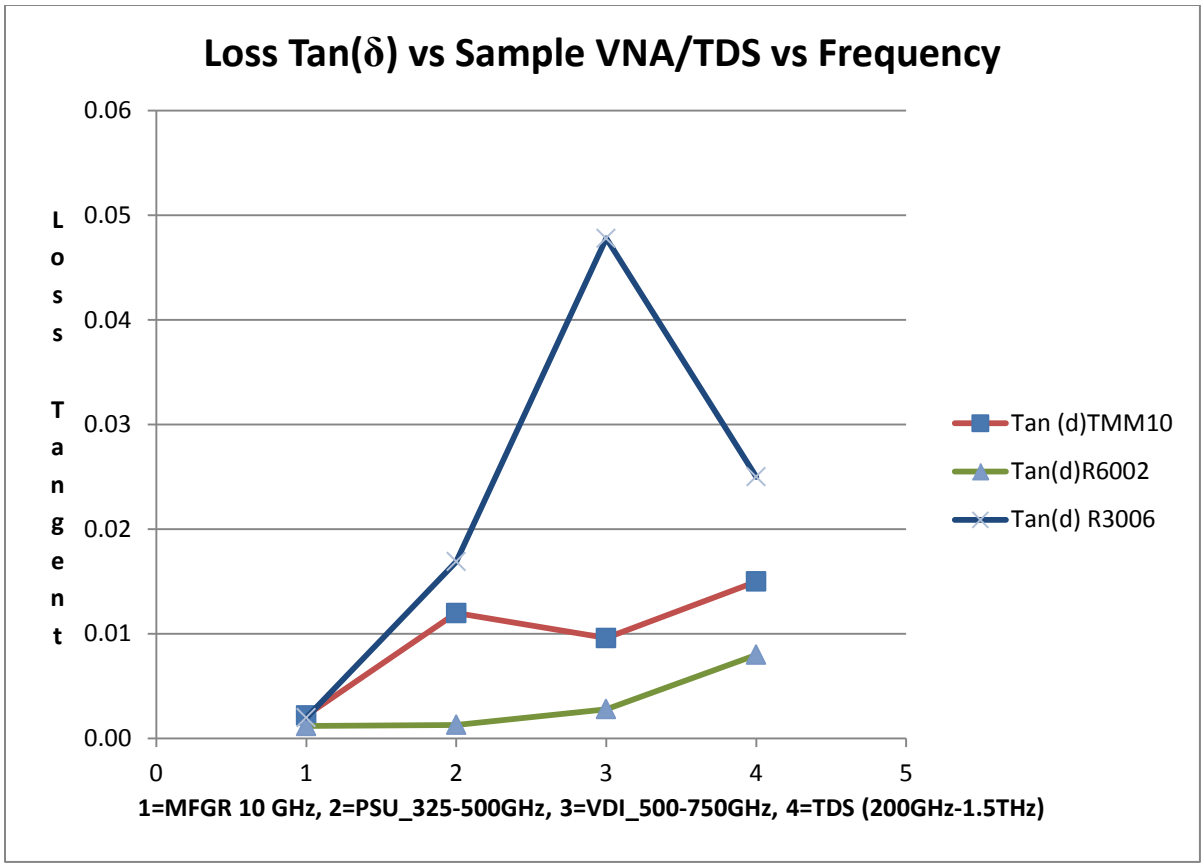
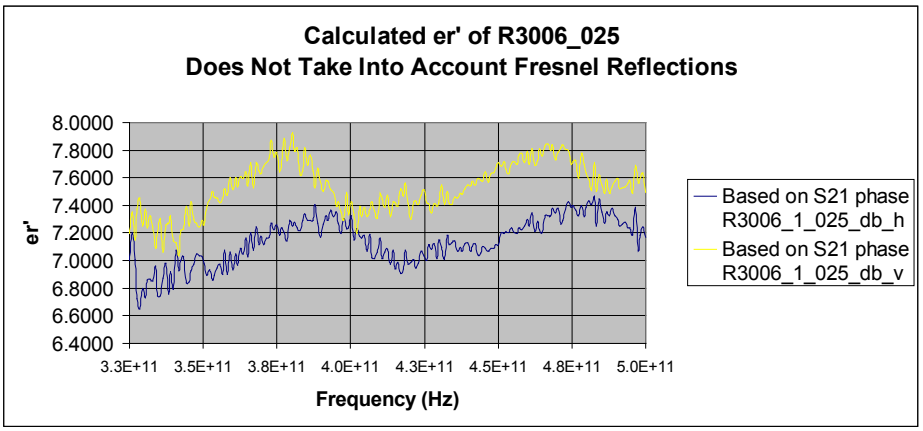
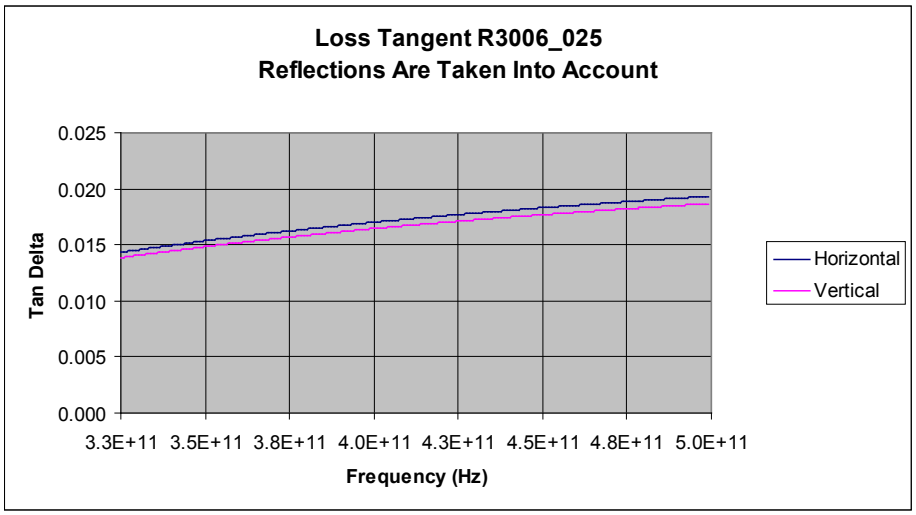


Figure 3 Loss Tangent, Tan (d), vs 3 Samples VNA/TDS vs Frequency

2.0 Some VNA Data Plots





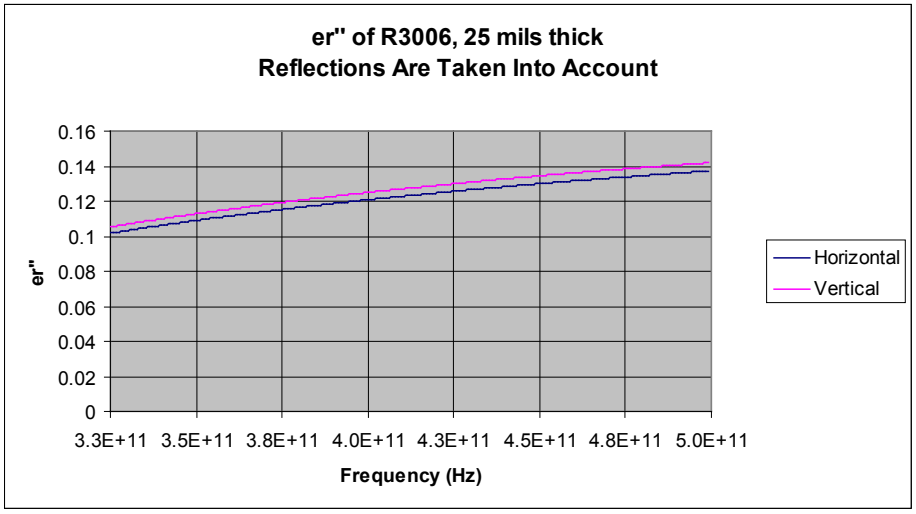


Figure 4 R3006 25 mils VNA Data (Measured at PSU)

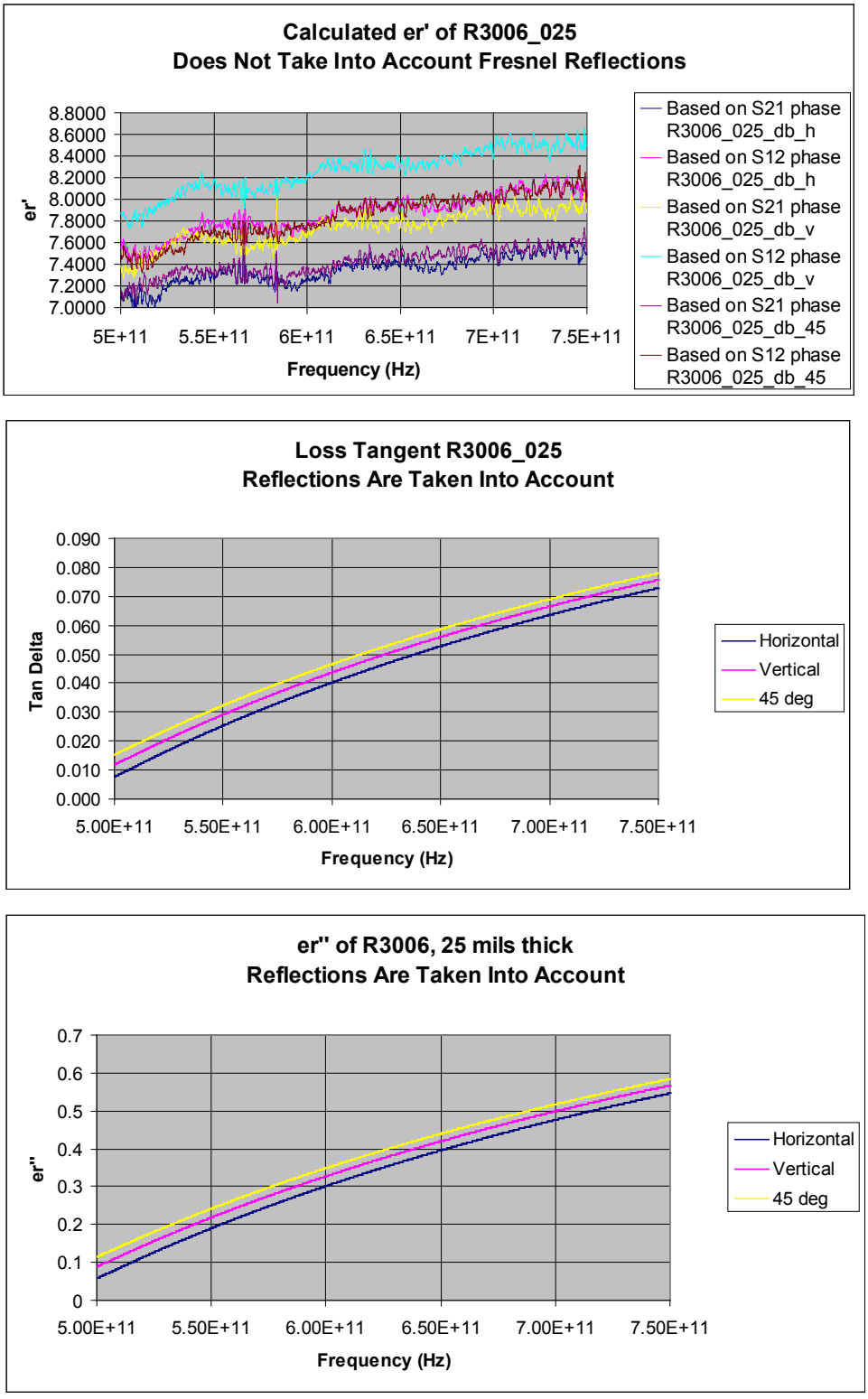
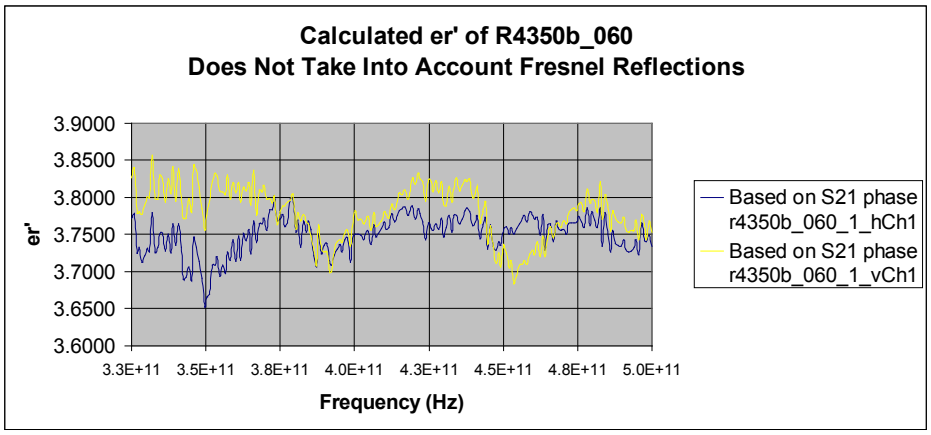
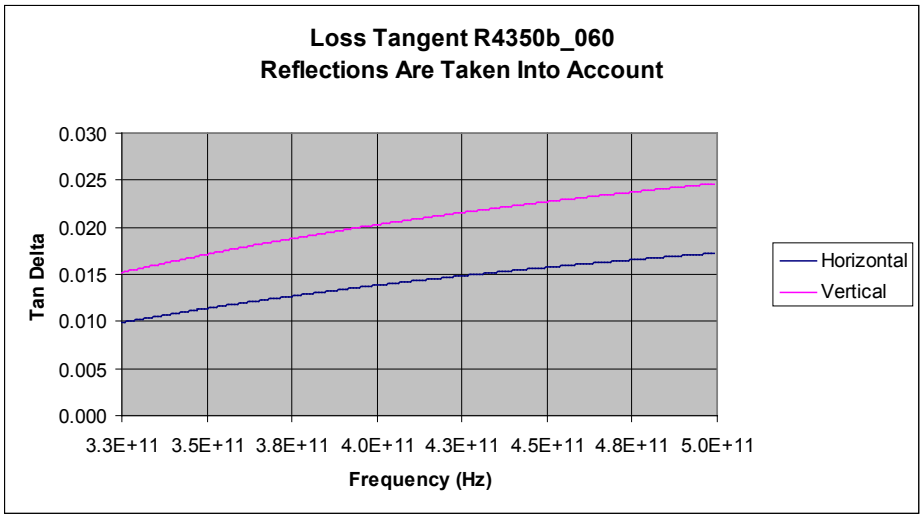


Figure 5 R3006 25 mils VNA Data (Measured at Virginia Diodes)





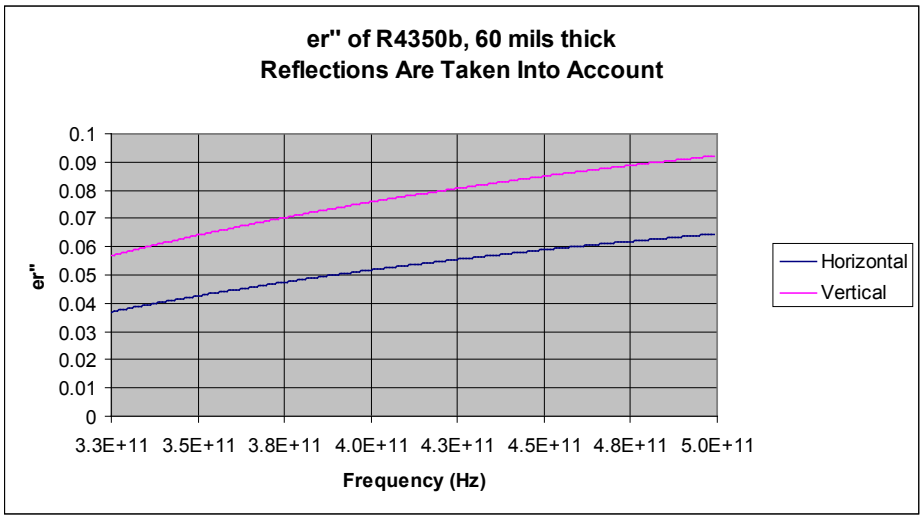
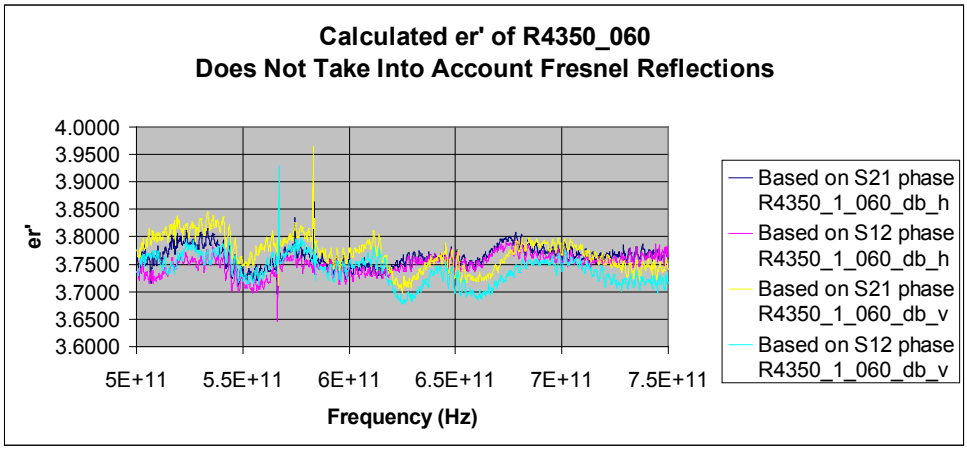
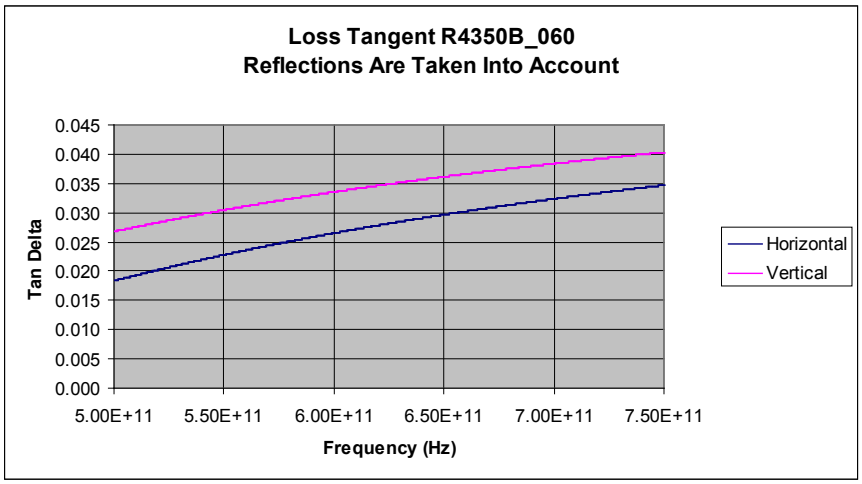


Figure 6 R4350B 60 mils VNA Data (Measured at PSU)





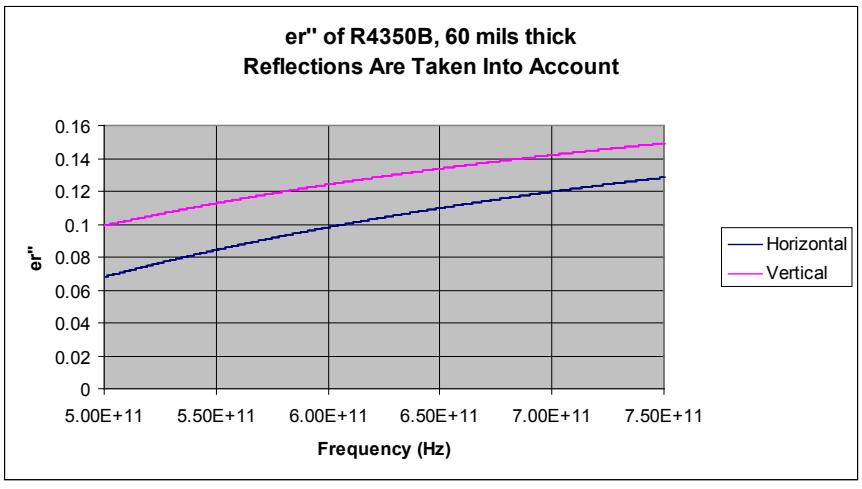
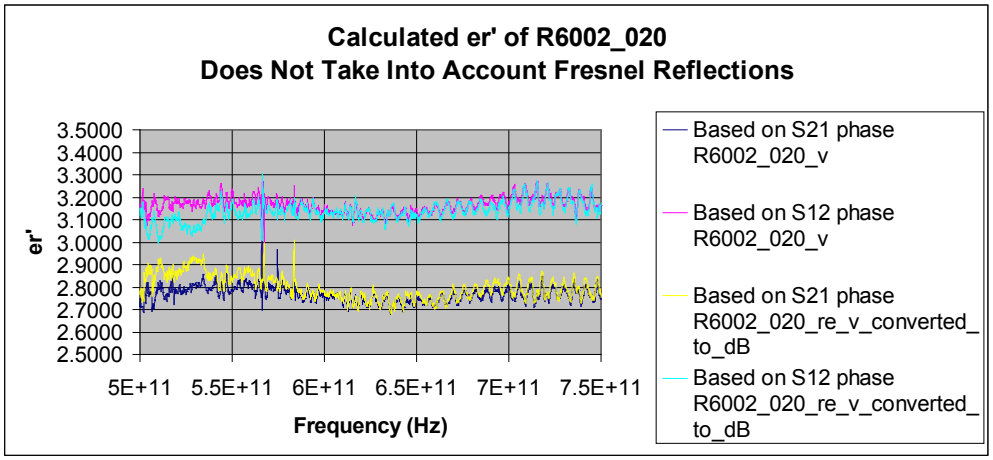
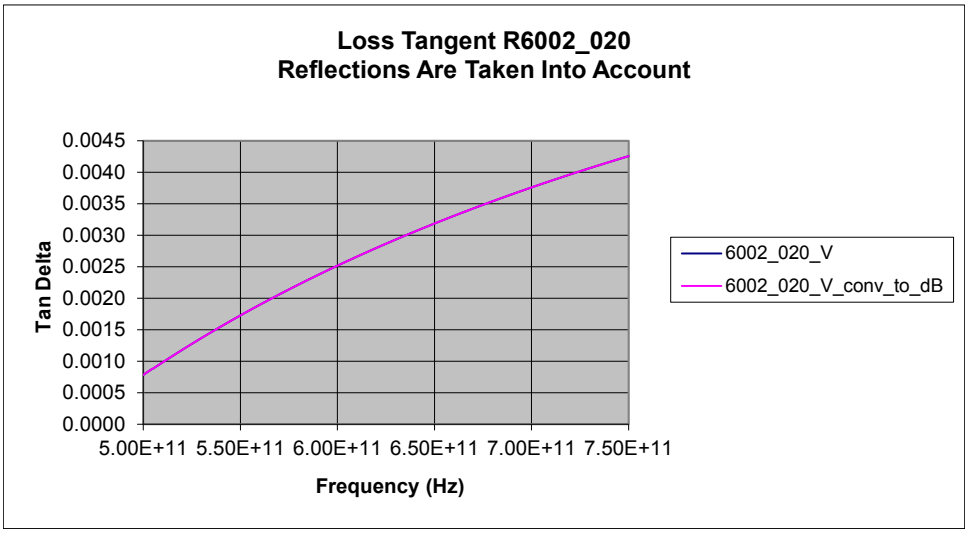


Figure 7 R4350B 60 mils er', er'', tanδ plots at VDI





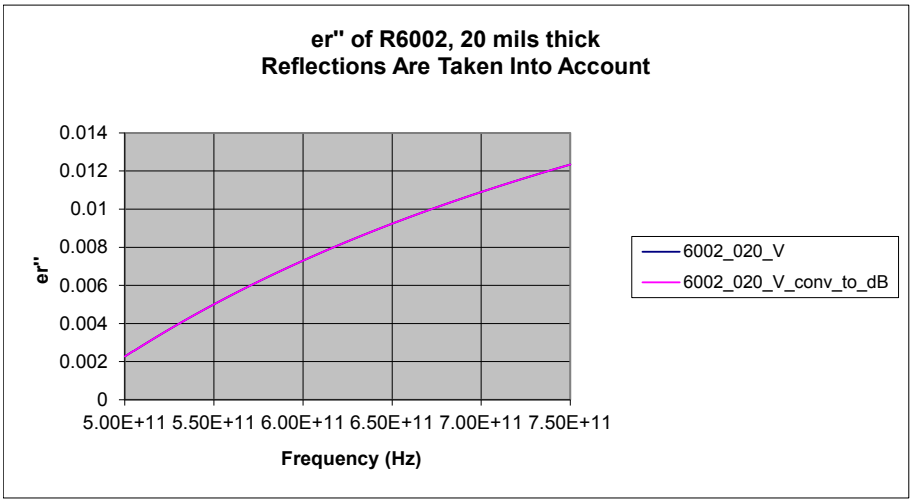
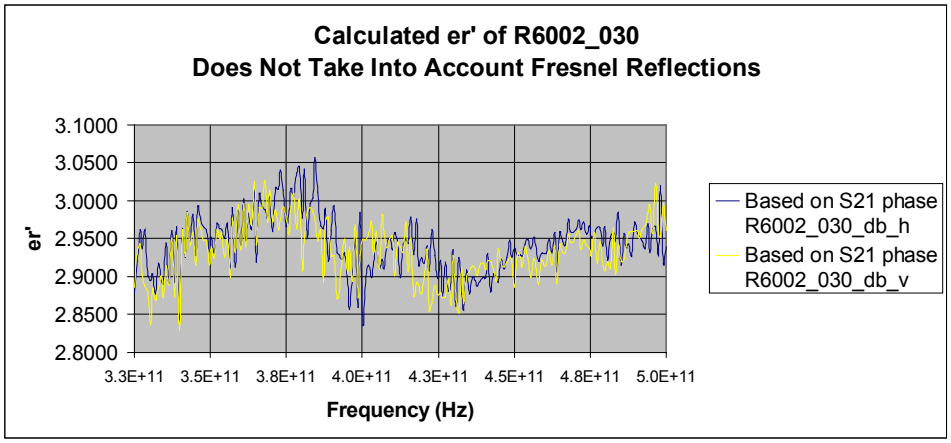
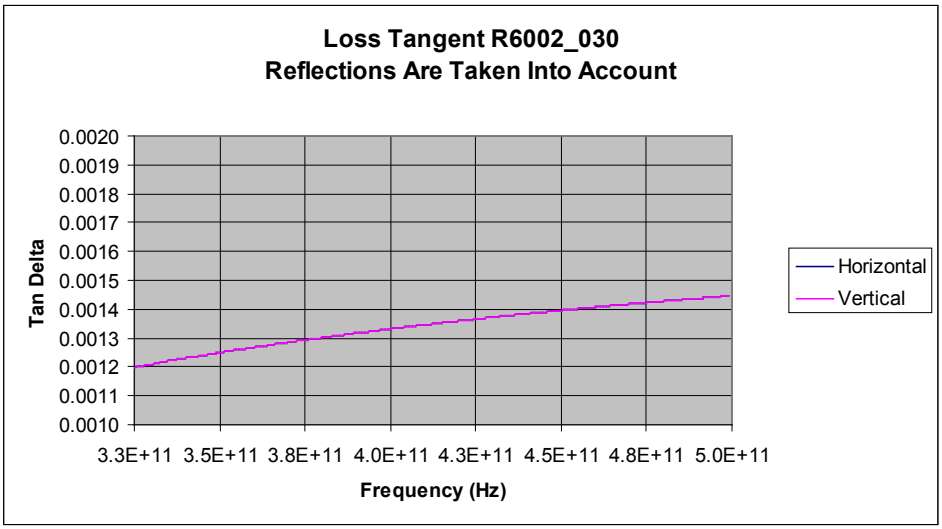


Figure 8 R6002 20 mils VNA Data overlap (Measured at Virginia Diodes)





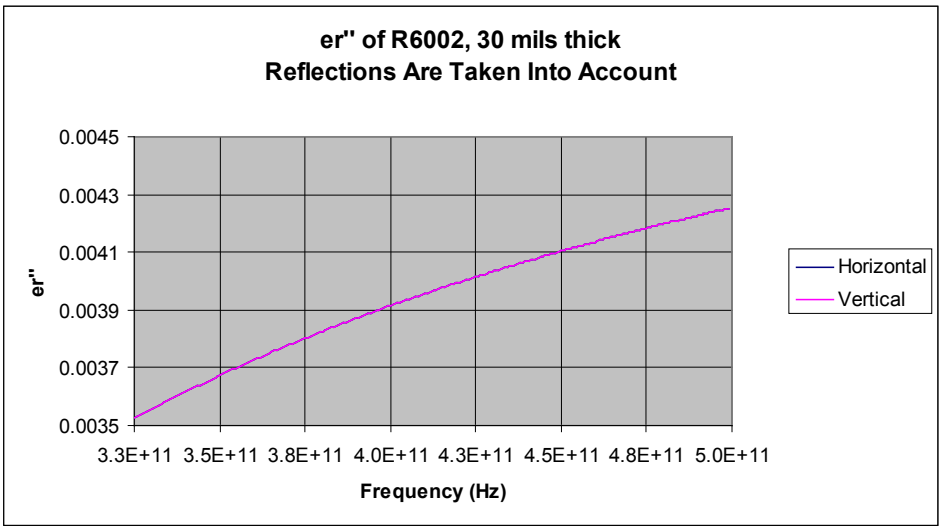


Figure 9 R6002 30 mils overlap VNA DATA (Measured at PSU)

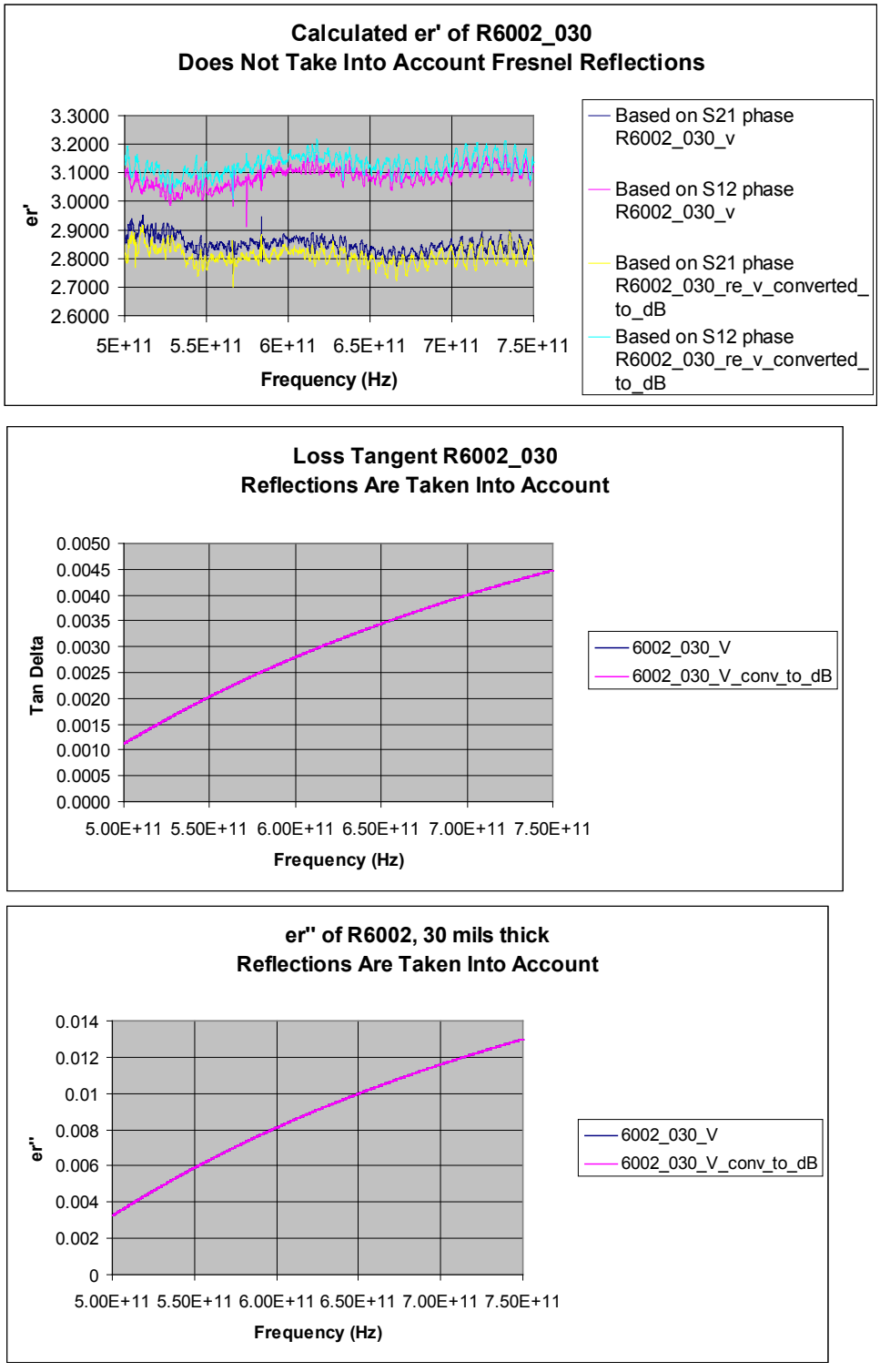


Figure 10 R6002 30 mils VNA DATA (Measured at Virginia Diodes)

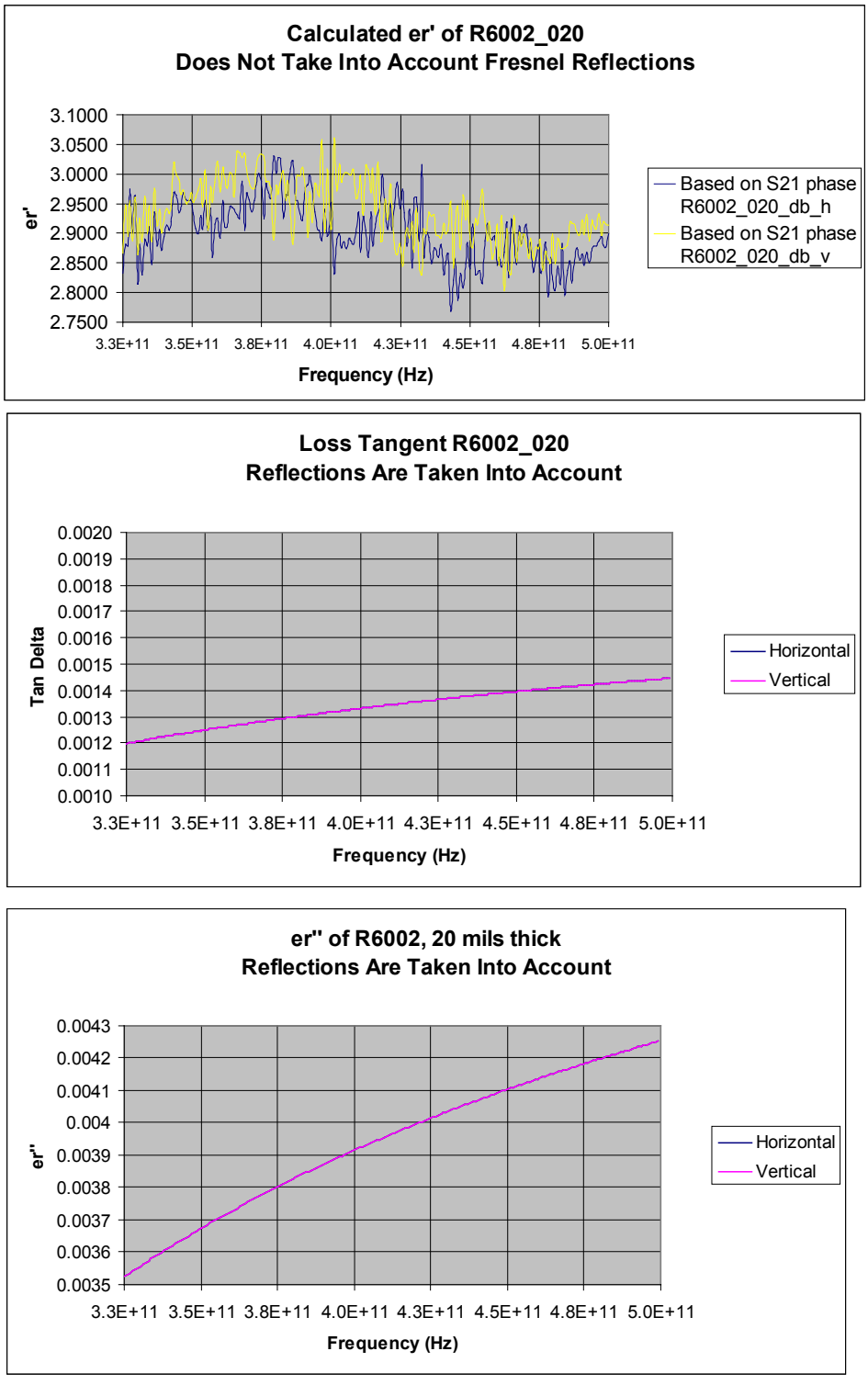
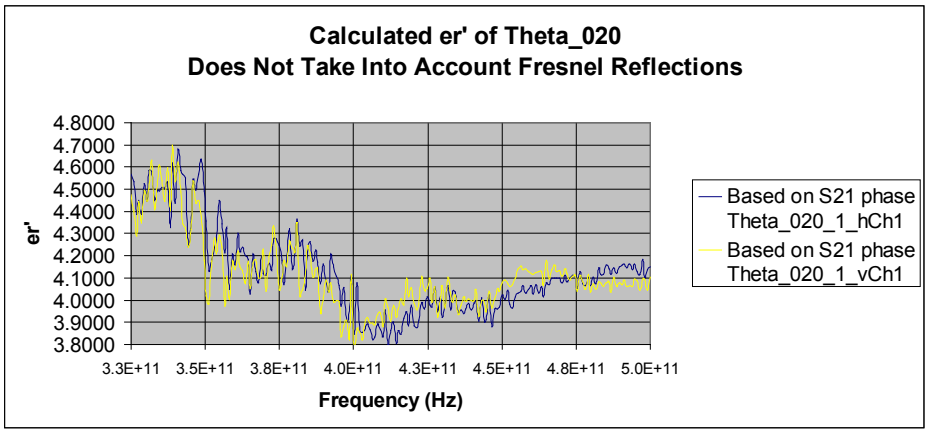
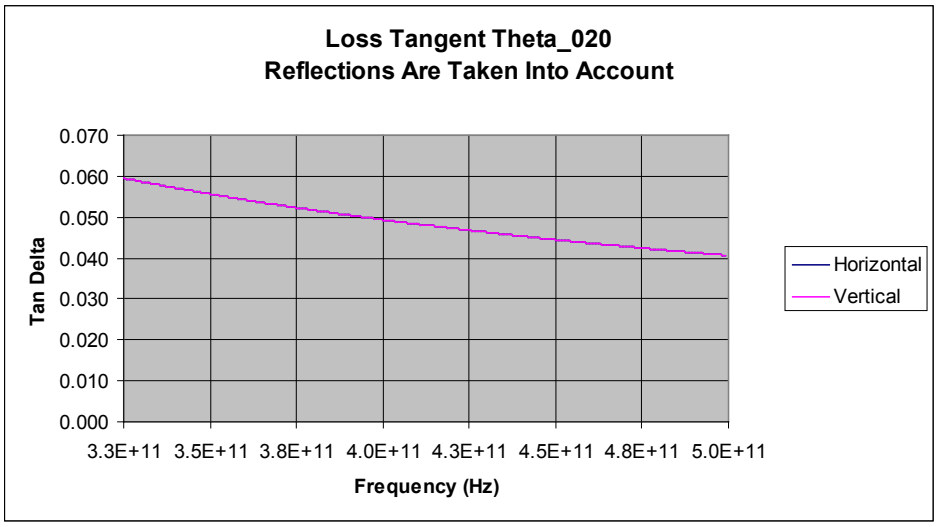


Figure 11 R6002 20 mils VNA DATA (Measured at PSU)





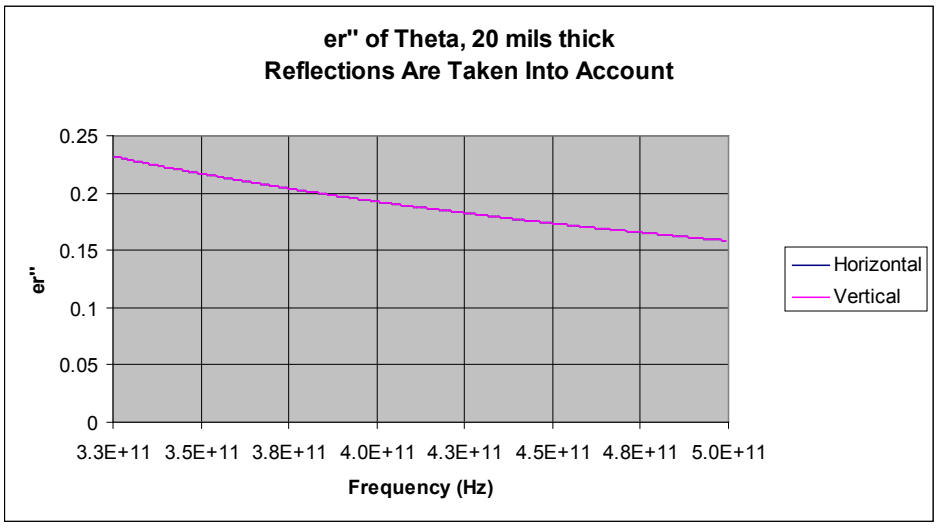


Figure 12 Theta 20 mils VNA DATA (Measured at PSU)

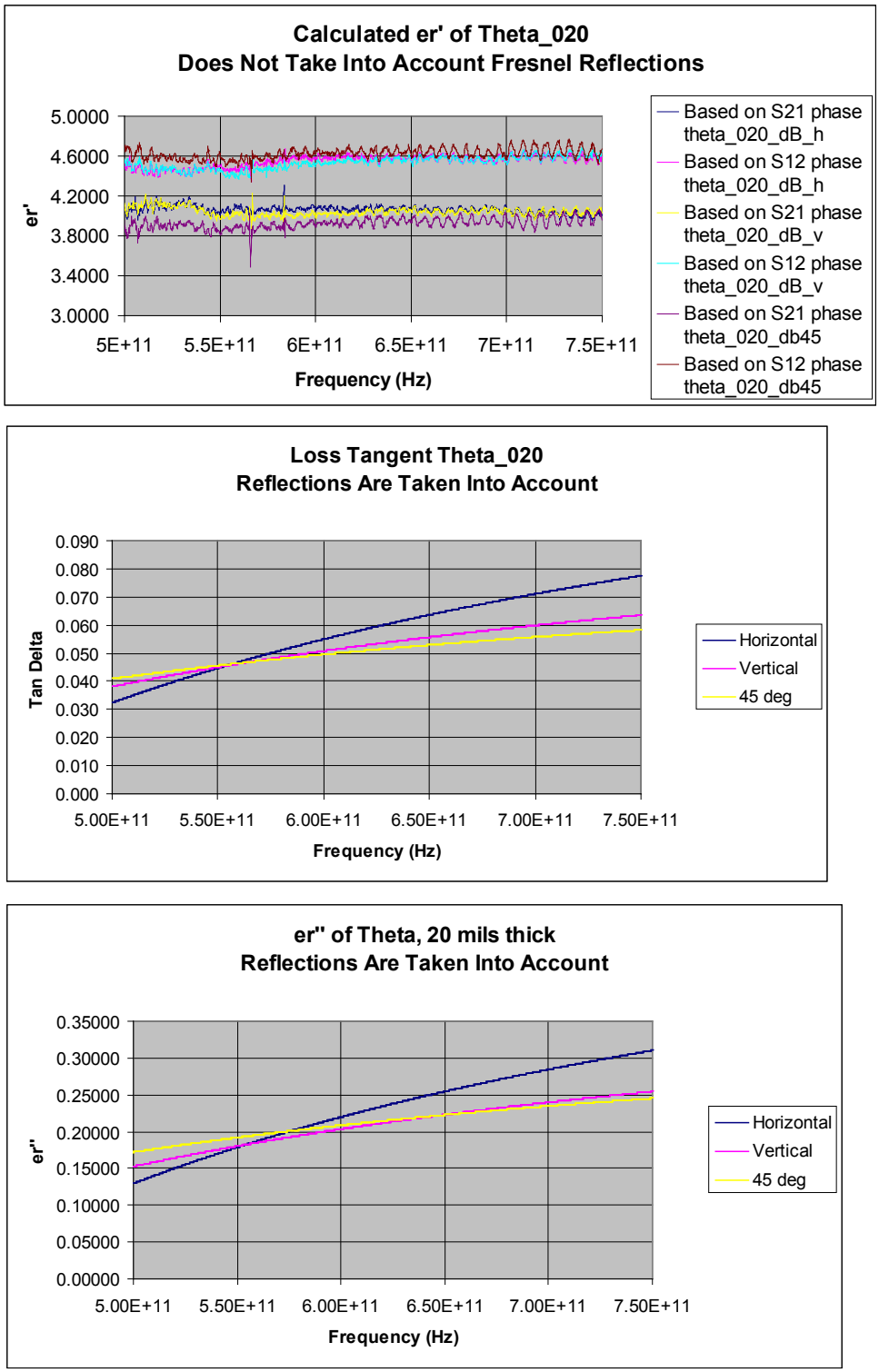
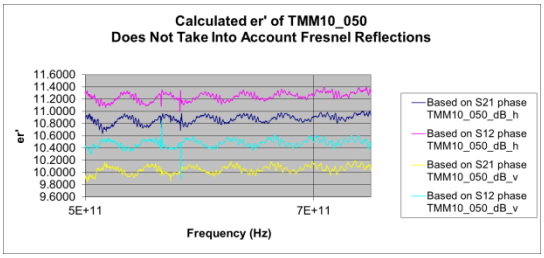


Figure 13 Theta 20 mils VNA DATA (Measured at Virginia Diodes)

Figure 14 TMM10_50_VDI



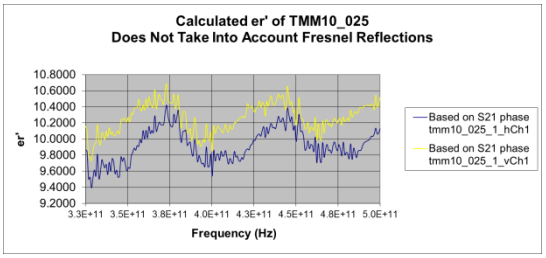


Figure 15 TMM10_25_PSU

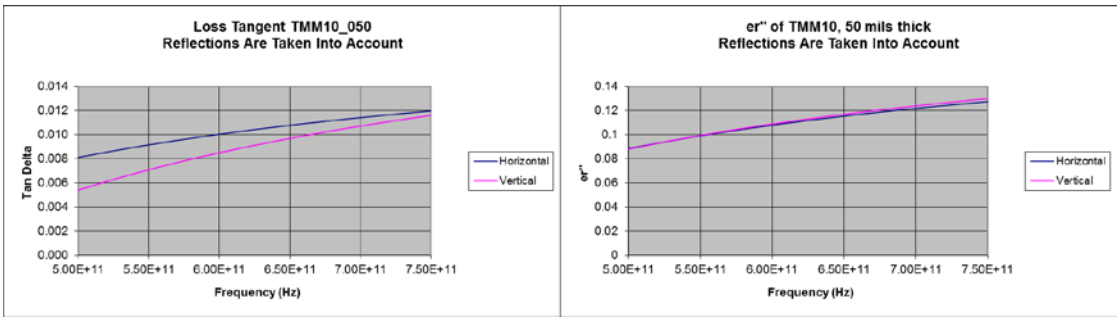


Figure 16 TMM10_050 at VDI

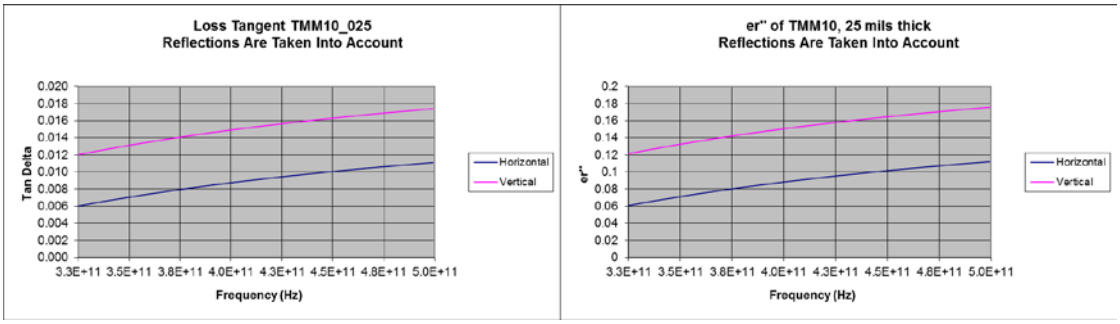


Figure 17 TMM10_25mil at PSU

FTS Data Summary using UA Astronomy Beckman FS720 Spectrometer												
Sample#	Mfgr (Thickness) caliper	Part/lot #	Description	Thickness (actual) Micrometer	ε_r / Loss [3]	Average Relative Level	Voltage (Scale factor) [1], [2] mV	*Scaled Average (mV)*	500GHz Relative Level	Scaled @ 500GHz (mV)	1 THz Relative level	Scaled @ 1 THz (mV)
1	Rogers (0.0260)	2012159	**TMM10**	**0.025**/(0.0266)	9.2/**0.0022**	5.00	1.18	***5.90***	7	**8.26**	1	**1.18**
1, pol	Rogers (0.0510)	2011993	**TMM10**	**0.05**/(0.05085)	9.2/**0.0022**	2.50	1.58	***3.95***	4	**6.32**	1	**1.58**
1	Rogers (0.0195)	3025938	**Theta**	**0.02**/(0.0197)	4.01/**0.0118**	0.65	4.31	***2.80***	0.75	**3.2325**	0.25	**1.0775**
1	Rogers (0.0100)	3018414	**Theta**	**0.01**/(0.01055)	4.01/**0.0118**	0.50	11.60	***5.80***	0.5	**5.8**	0.3	**3.48**
1	Rogers (0.0205)	2007683	**R4350B**	**0.02**/(0.01995)	3.66/**0.0037**	0.50	12.30	***6.15***	0.75	**9.225**	0.5	**6.15**
1	Rogers (0.0100)	2007680	**R4350B**	**0.01**(0.0102)	3.66/**0.0037**	1.00	9.00	***9.00***	0.75	**6.75**	0.45	**4.05**
1	Rogers (0.0205)	3015151	**R3003**	**0.02**/(0.02045)	3.00/**0.0013**	0.80	13.00	***10.40***	0.8	**10.4**	0.4	**5.2**
1, pol	Rogers (0.0100)	3014902	**R3003**	**0.01**/(0.01015)	3.00/**0.0013**	0.70	18.00	***12.60***	0.8	**14.4**	0.45	**8.1**
1	Rogers (0.0205)	2020435	**R6002**	**0.02**/(0.02035)	2.94/**0.0012**	0.75	24.80	***18.60***	1	**24.8**	0.9	**22.32**
1	Rogers ((0.0105)	2010668	**R6002**	**0.01**/(0.01075)	2.94/**0.0012**	1.00	28.20	***28.20***	1	**28.2**	0.85	**23.97**

Samples arranged in order of Relative Loss and corresponding manufacturer data

Notes

(1) 1.1 mil Beam Splitter/Filter used for TMM10 Measurement (SF correction 3.5)

(2) 7.4 mil Beam Splitter/Filter used and set as reference using R6002

(3) Rogers Corp. Loss Tangent @ 10 GHz using method IPC-TM-650-2.5.5.5C (ipc.org)

Er, using stripline resonant Method

TMM™10 = thermoset microwave materials are ceramic, hydrocarbon, thermoset polymer composite resin

THETA = MCL-HE-679G Laminate, GHA-679G Prepreg, Halogen Free (FR4 replacement)

RO4350B™ = proprietary woven glass reinforced hydrocarbon/ceramic (replaces PTFE/woven glass)

RO3003™ = high frequency circuit materials are ceramic-filled PTFE composites

R6002 = RT/duroid™ Laminates

Figure 18 Updated FTS Data

In=I0 exp(-α dn), where In is Intensity (power, uW) or $(mV)^2$, dn = sample thickness, and α= absorption coefficient, this is also designated by many authors as "k".

Beer's Law calculations are in the table below

k or α= abs [ln (I2)-ln (I1) / (d1-d2)], (per length, inch), and $I_{1,2} = (V_{1,2})^2$, amplitude squared for each thickness.

$I_0 = I_{1,2} \exp(k*d_{1,2}) = (V_{1,2})^2 \exp(k*d_{1,2})$, for two different thicknesses of the same material.

Material	Thickness (mils)	Amplitude (mV)	Intensity (uW)	Amplitude Ratio	k (exper) Absorption	I_0 (uW)	V (calc)	Beers Ratio (calc)	Experimental Ratio	k (mfgr), er'xDf	k%(error)
Theta (avg)	19.7	2.8	7.84			180.375678	2.8	2.071428571	2.071428571	**4.01**	
Theta*	10.55	5.8	33.64			180.375678	5.8			**0.0118**	
Delta and k	9.15			2.071428571	**0.159177814**					**0.047318**	236.4001
Theta 500G	19.7	3.2325	10.44906			129.5173222	3.2325	1.794276875	1.794276875	**4.01**	
Theta 500G	10.55	5.8	33.64			129.5173222	5.8			**0.0118**	
Delta and k	9.15			1.794276875	**0.127781877**					**0.047318**	170.0492
Theta 1THz	19.7	1.0775	1.161006			180.8387698	1.0775	3.229698376	3.229698376	**4.01**	
Theta 1THz	10.55	3.48	12.1104			180.8387698	3.48			**0.0118**	
Delta and k	9.15			3.229698376	**0.256259836**					**0.047318**	441.5695
TMM10(avg)	50.85	3.95	15.6025			83.94348068	3.95	1.493670886	1.493670886	**9.2**	
TMM10	26.6	5.9	34.81			83.94348068	5.9			**0.0022**	
Delta and k	24.25			1.493670886	**0.033091693**					**0.02024**	63.4965
TMM10 500G	50.85	6.32	39.9424			122.7494272	6.32	1.306962025	1.306962025	**9.2**	
TMM10 500G	26.6	8.26	68.2276			122.7494272	8.26			**0.0022**	
Delta	24.25			1.306962025	**0.022078794**					**0.02024**	9.084951
TMM10 1THz	50.85	1.58	2.4964			8.491517964	1.58	0.746835443	0.746835443	**9.2**	
TMM10 1THz	26.6	1.18	1.3924			2.641709233	1.18			**0.0022**	
Delta	24.25			0.746835443	**0.024075085**					**0.02024**	18.94805
R4350B#*	19.95	6.15	37.8225			179.6736907	6.15	1.463414634	1.463414634	**3.66**	
R4350B*	10.2	9	81			179.6736907	9			**0.0037**	
Delta	9.75			1.463414634	**0.078107179**					**0.013542**	476.7773
R4350B	20	6.15	37.8225			173.4681737	6.15	1.463414634	1.463414634	**3.66**	
R4350B	10	9	81			173.4681737	9			**0.0037**	
Delta	10			1.463414634	**0.076154499**					**0.013542**	462.3578
R3003	20	10.4	108.16			233.0319675	10.4	1.211538462	1.211538462	**3**	
R3003	10	12.6	158.76			233.0319675	12.6			**0.0013**	
Delta	10			1.211538462	**0.038378202**					**0.0039**	884.0565
R3003*	19.95	10.4	108.16			237.1964403	10.4	1.211538462	1.211538462	**3**	
R3003*	10.2	12.6	158.76			237.1964403	12.6			**0.0013**	
Delta	9.75			1.211538462	**0.039362258**					**0.0039**	909.2887
R6002	30	18.6	345.96			4201.872527	18.6	1.516129032	1.516129032	**2.94**	
R6002	20	28.2	795.24			4201.872527	28.2			**0.0012**	
Delta	10			1.516129032	**0.083232079**					**0.003528**	2259.186
R6002*	10.75	18.6	345.96			878.6169743	18.6	1.516129032	1.516129032	**2.94**	
R6002*	20.35	28.2	795.24			4642.418045	28.2			**0.0012**	
Delta	9.6			1.516129032	**0.086700083**					**0.003528**	2357.485
R6002 500GHz	10.75	24.8	615.04			820.0991284	24.8	1.137096774	1.137096774	**2.94**	
R6002 500GHz	20.35	28.2	795.24			1371.058736	28.2			**0.0012**	
Delta	9.6			1.137096774	**0.026766318**					**0.003528**	658.6825
R6002 1THz	10.75	22.32	498.1824			584.4628141	22.32	1.073924731	1.073924731	**2.94**	
R6002 1THz	20.35	23.97	574.5609			777.4138256	23.97			**0.0012**	
Delta	9.6			1.073924731	**0.014858315**					**0.003528**	321.154

Figure 19 Beer's Law Analysis of FTS Data

3.0 Updated Dissertation Figures

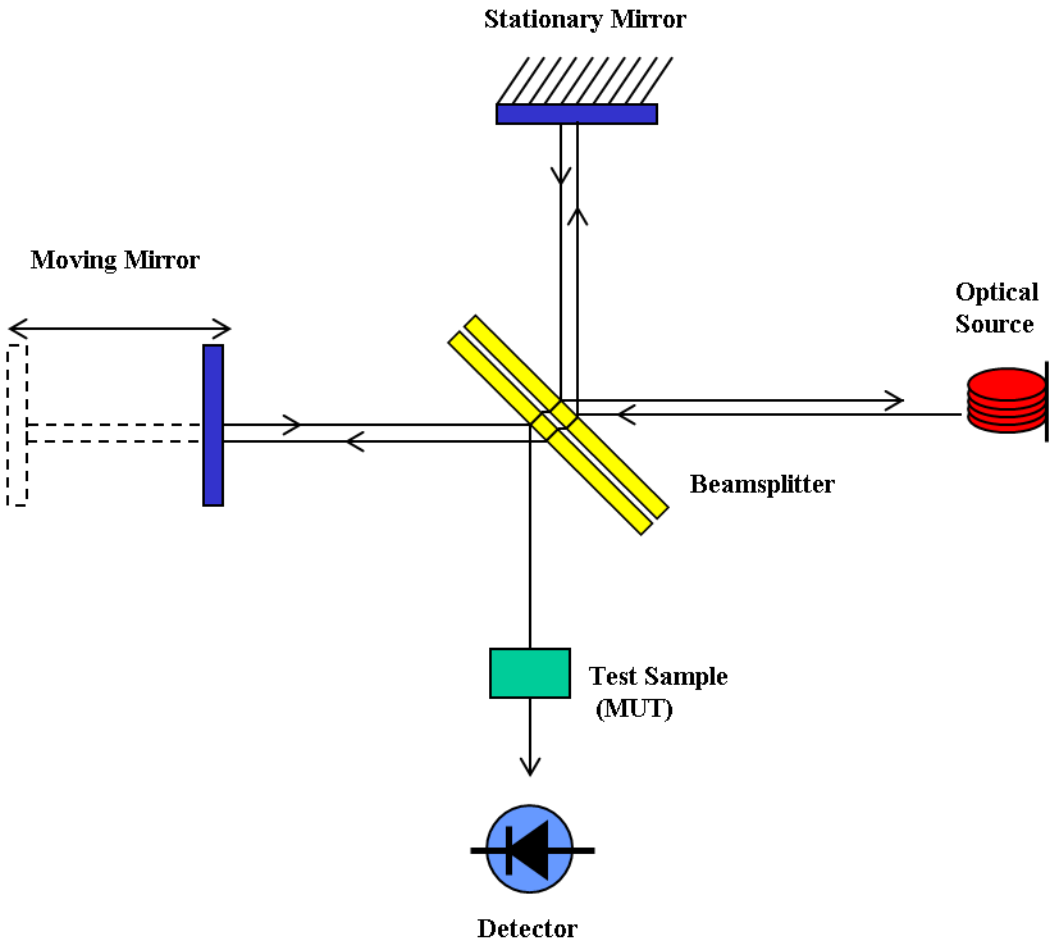


Figure 20 Basic FTS System

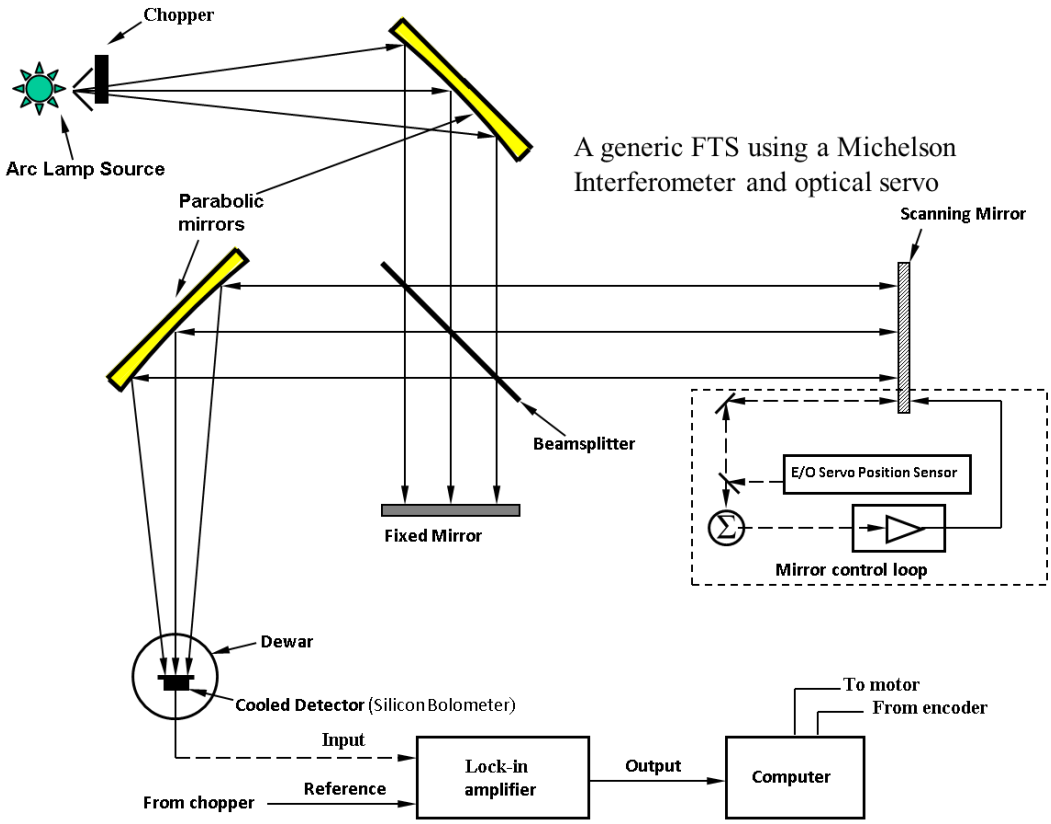


Figure 21 Modern FTS System

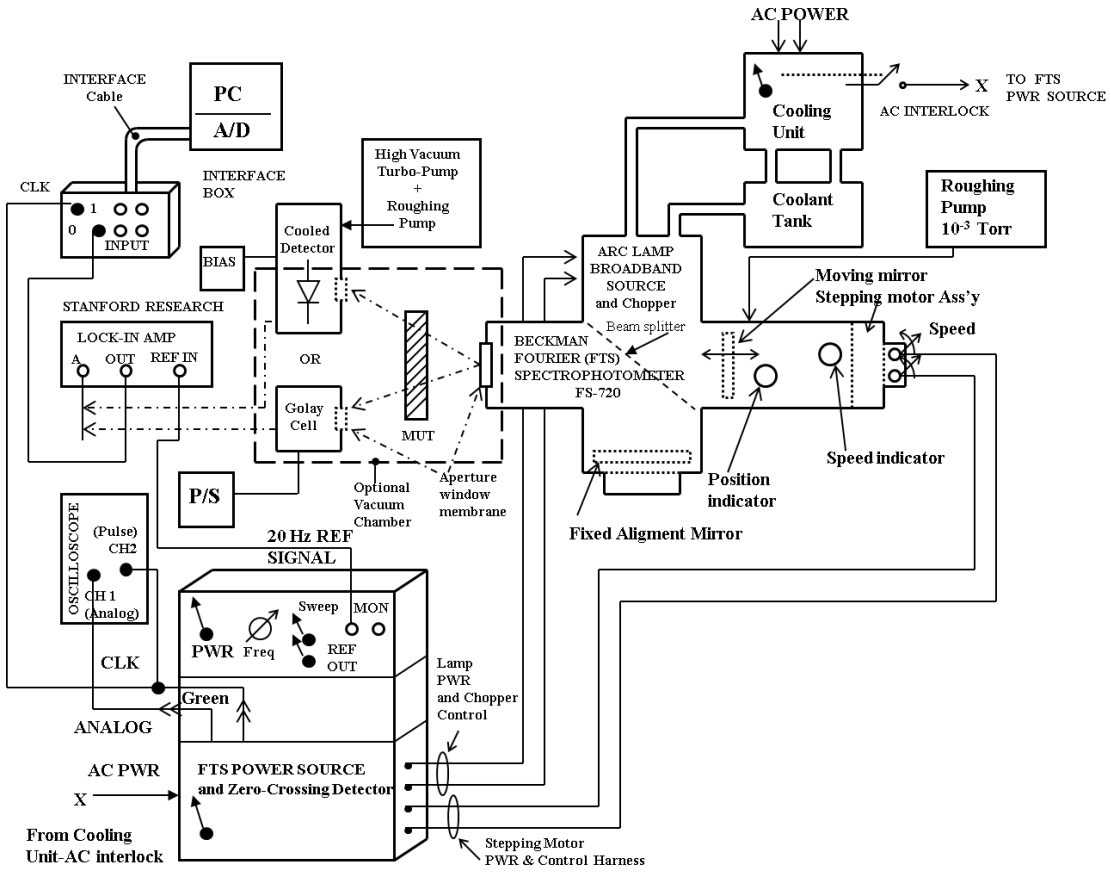


Figure 22 UA FTS System Showing Beam Splitter

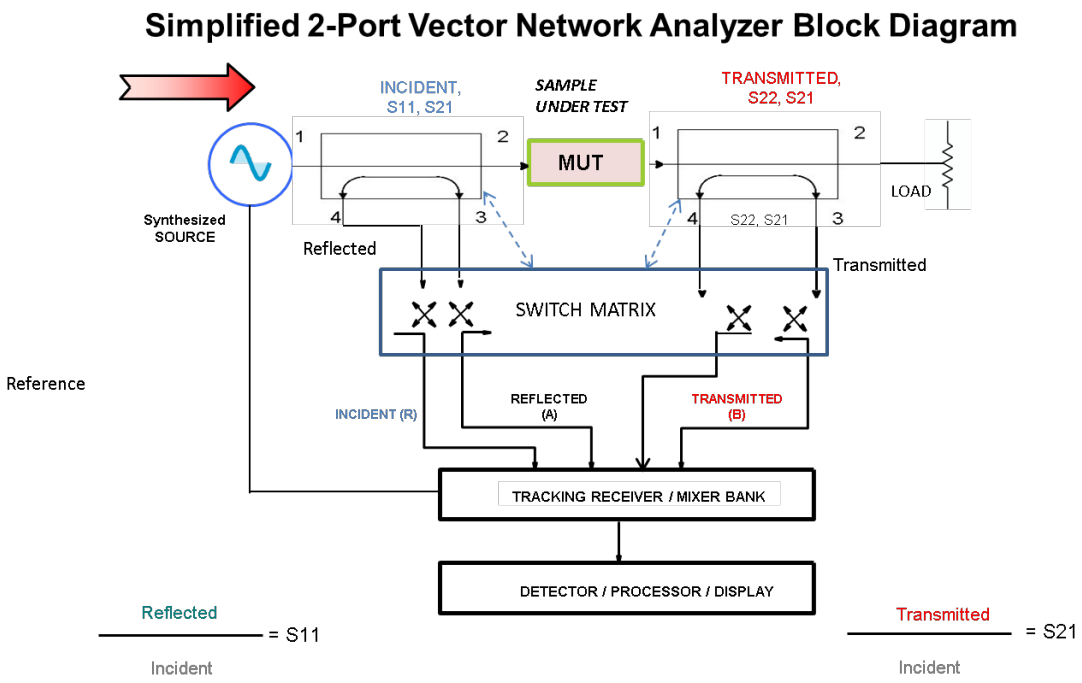


Figure 23 Two Port Vector Network Analyzer

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