Modeling and Measurement of Dual-Circular Polarized Feed for Prime Focus Antenna

by Jeffrey Pawlan

with modeling and feed design by

Rastislav Galuscak

Outline

- When was it invented and improved?
- What is a septum feed?
- Simulations of the feed alone
- Simulations of the feed with 10 lambda dish
- Simulations of the feed with 12 foot dish
- Measurement issues
  - VNA Calibration with two connector types

History of the Septum Feed

- Described in MIT Rad Lab vol 9 by G.L. Ragan
- Experimental and military work by Bill Parris at Westinghouse (ca 1965)
- AP-S Symposium presentation by his fellow workers: D. Davis, O. J. Digiondomenico, J. A. Kempic in 1967
- Chen and Tsandoulas refine the calculations 1973
- Schrank describes its many uses 1982-3
- Behe and Brachat create the first circular waveguide version in 1991

History of the Septum Feed

- Radio astronomers and amateur radio operators in the Czech Republic manufacture and deploy them for radio astronomy and space communications
- Mathematically difficult to optimize the steps
- By 2004 3D EM software improved to become capable of some simulations of the septum feed
- By 2006 it was possible to optimize the septum steps using mode matching
- In 2009 we successfully simulated the entire feed and also at the prime focus of large dishes

Septum Feed

- A sloping or a stepped septum is placed in the H-plane of a waveguide (circular or rectangular)
  - Perpendicular (normal) field transforms into two even-mode signals
    - The two are equal and not affected by the septum
  - Parallel field transforms into two odd-mode signals
    - The septum changes the phase vectors so that they become back to back
    - Septum acts like a ridged wavequide and lowers the cutoff frequency
    - Guide w/l becomes longer so introduces a delay
- Goal is 90 degree differential phase

Figure 1

Septum in Circular Waveguide from Rad Lab

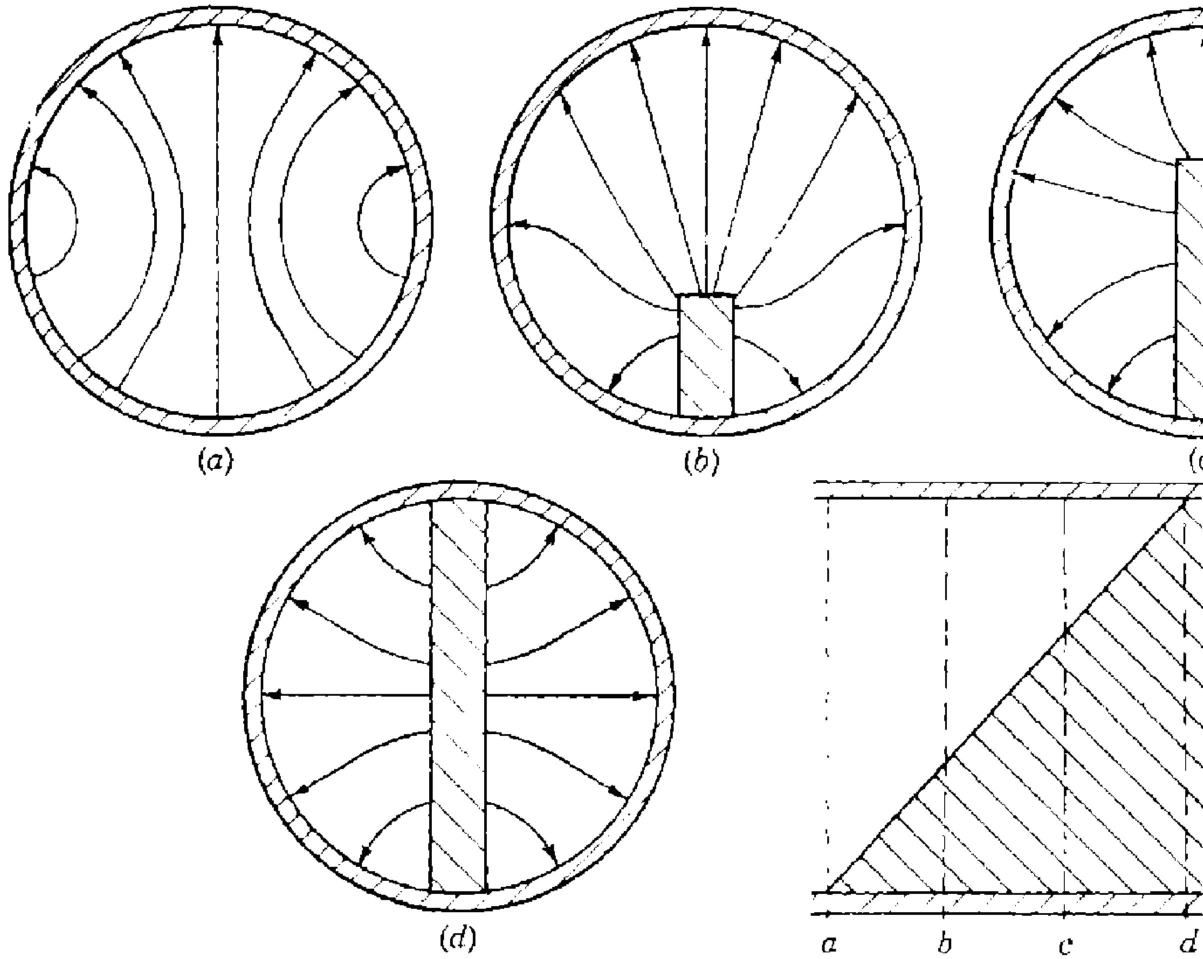


FIG. 6·100. — Field configurations in round waveguide with tapered fin.

Septum in Square Waveguide from Davis, Digiondomenico, & Kempic

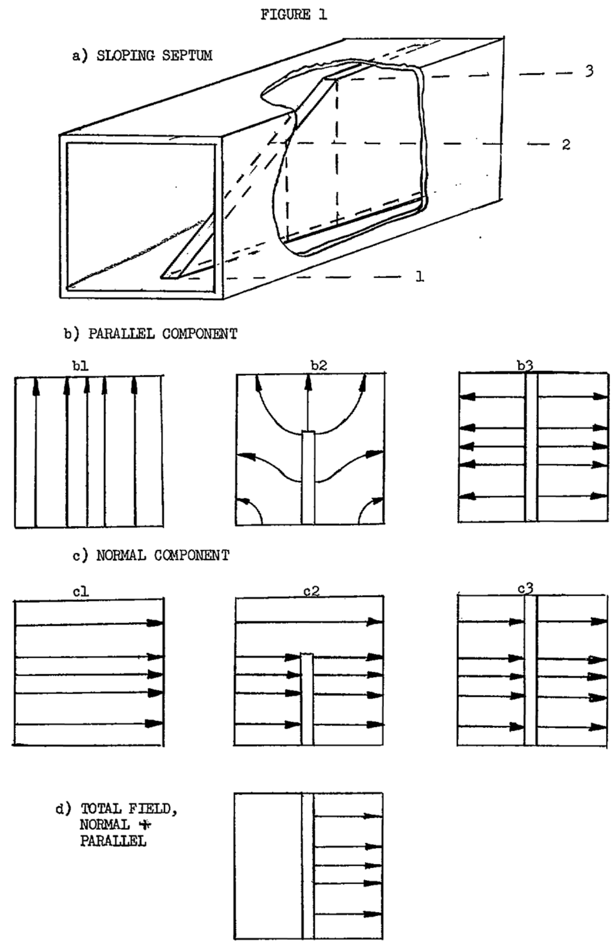
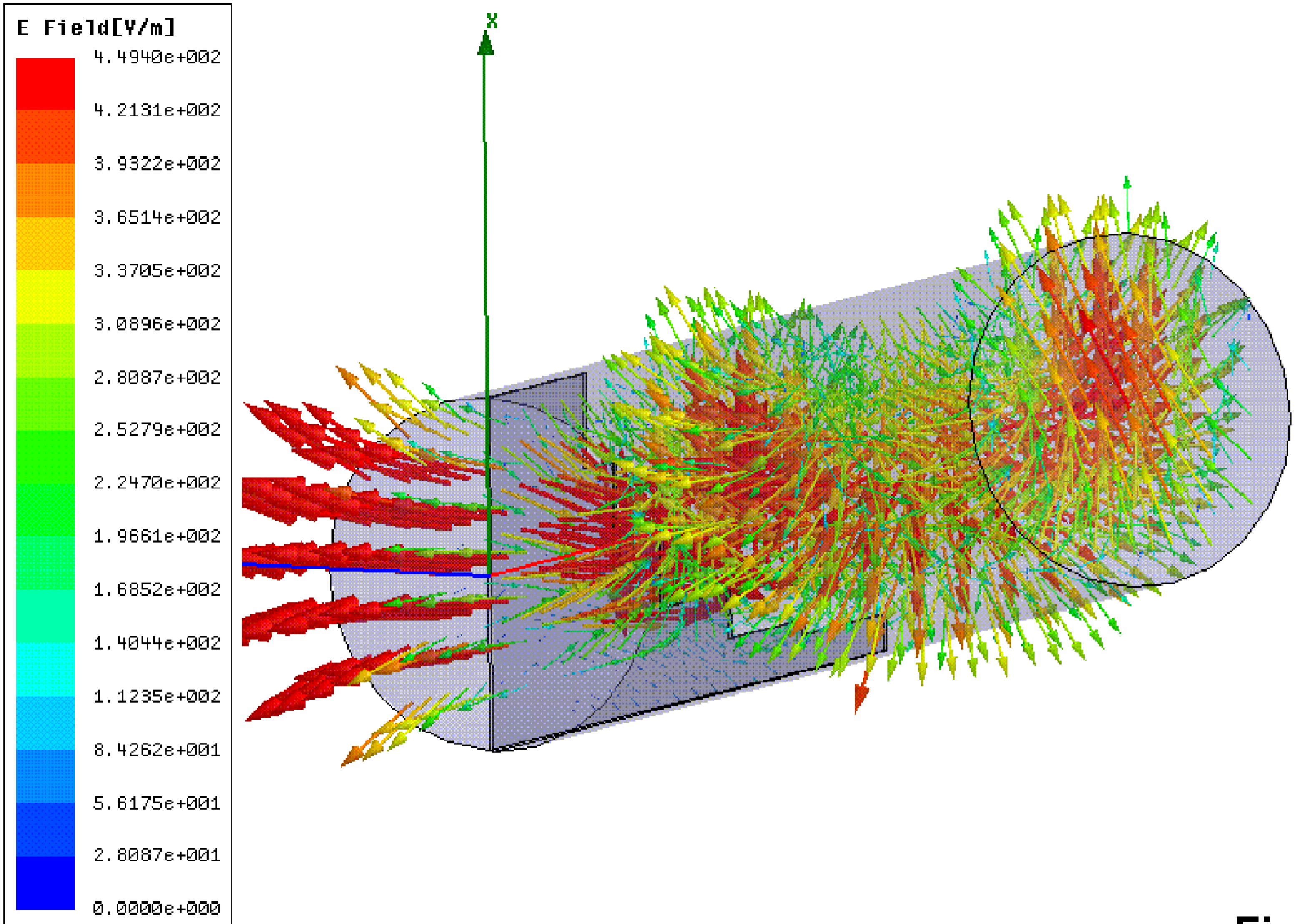


Figure 2



E Field[V/m]
4.4940e+002
4.2131e+002
3.9322e+002
3.6514e+002
3.3705e+002
3.0896e+002
2.8087e+002
2.5279e+002
2.2470e+002
1.9661e+002
1.6852e+002
1.4044e+002
1.1235e+002
8.4262e+001
5.6175e+001
2.8087e+001
0.0000e+000
X

Figure 3

Figure 4

Compact Duplexer–Polarizer with Semicircular Waveguide

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 39, NO. 8, AUGUST 1991

Roger Behe and Patrice Brachat

Abstract—**Circularly polarized antennas such as C-band space communications antennas are generally fed by rotationally symmetric structures radiating the two strongly decoupled orthogonal polarizations. A light, compact, and high-performance device able to generate circularly polarized waves in a circular waveguide, is discussed.**

I. Introduction

Several technologies are currently used to excite high purity left-hand or right-hand circular polarizations in a circular waveguide.

The association of several distinct devices such as orthomode transducers (OMT), polarizers and square-to-circular waveguide transitions is too bulky for tightly packed feed arrays (multibeam or contoured beam antennas).

The use of a probe excitation in a circular waveguide requires hybrid circuits in coaxial or microstrip technology. Unfortunately, these circuits introduce significant losses (0.5 dB) and show poor isolation performances.

The stepped septum in a square waveguide [1], [2] is a very interesting device. It is an extremely compact element which handles the tasks of both the OMT and the polarizer. It appears difficult to increase the compactness of this component. The solution proposed here involves eliminating the square-to-circular waveguide transition required by the output-port cross section of this device, and keeping a circular cross section throughout.

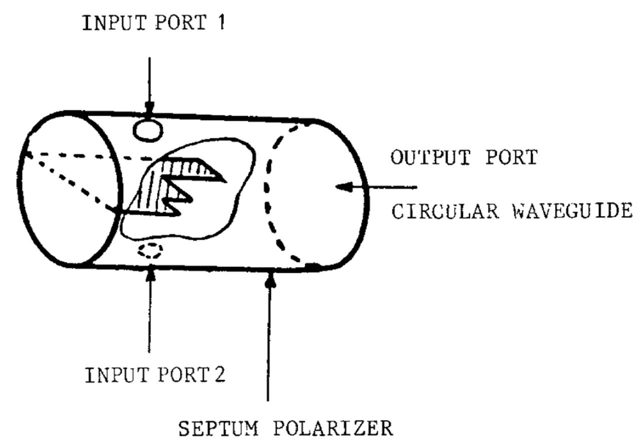
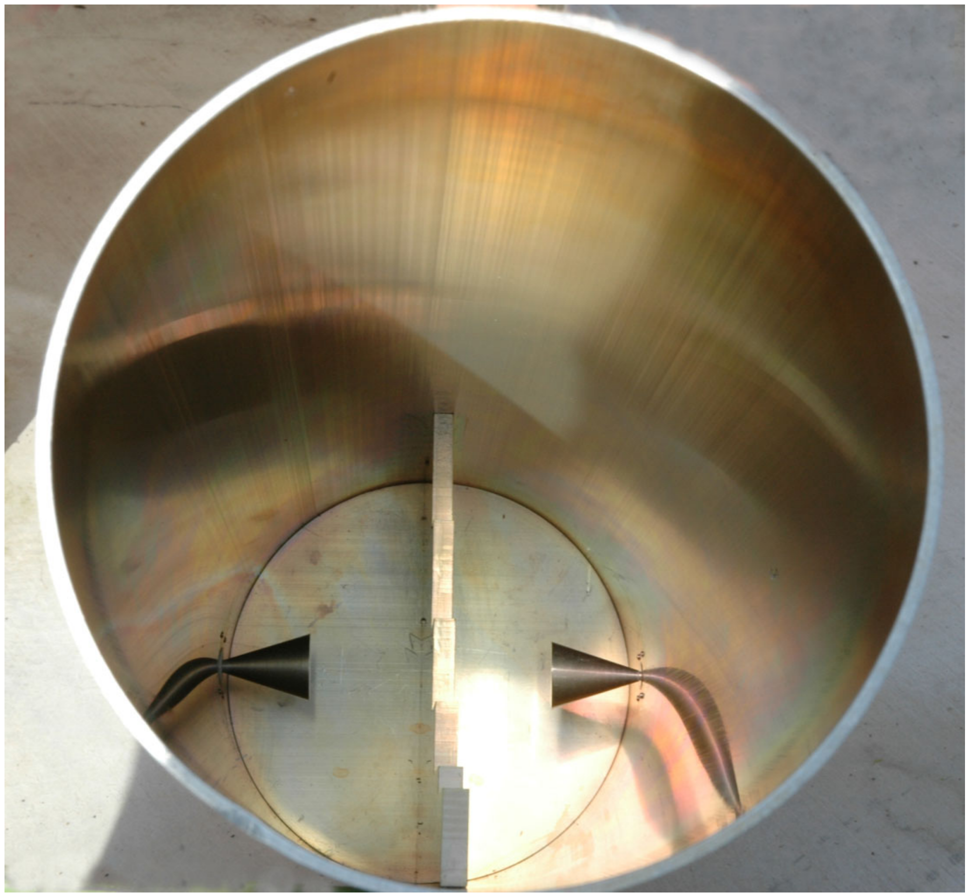


Fig. 1. Septum in circular waveguide.

Figure 5
New Septum Feed
Designed by Galuscak and Hazdra



Feed Details

- This particular feed designed for center frequency 1296MHz, application: Earth Moon Earth (EME) communications
- Pattern and axial ratio already measured in anechoic chamber at Czech Technical University. Actual measurement data:
  - 8.6dB gain
  - 0.2dB axial ratio (circularity)
- Port 1 is a ‘N’ for receive, Port 2 is DIN 7-16 for transmit

Simulation Details

- Simulation Program and Computer
  - CST Microwave Studio 2009
  - Windows XP 64 bit OS
  - Supermicro server MB
  - 2 Quad core Xeon processors (8 cores)
  - 64GB ECC memory
- Structure was created on another program and imported as a SAT file

Simulation Details continued

- The same feed structure was simulated six times, each with different solver or mesh settings.
- Feed alone in vacuum was done first
- All simulations were done with the Transient (“T”) solver for best accuracy of s-parameters
- Six simulations were run with identical structure
- Fast Perfect Boundary Approximation (FPBA) was used in place of PBA for one of the six simulations. You will see a reduction in accuracy

* Transient Solver Settings

Sim.	Accuracy	Sub-cycles	Fill limit	PBA timestep	Stability factor	AR filter
* 1	-40dB	4	70	.45	.9	No
* 2	-60	4	70	.45	1	No
* 3	-40	4	70	.45	1	no
* 4	-40	4	70	.45	1	no
* 5	-60	4	70	.45	1	yes
* 6	-40	4	70	.45	1	yes

* Mesh Settings

Sim	Lines/ wavelength	Lower Mesh Limit	Mesh line ratio	PBA or FPBA	PBA fill limit
* 1	26	5	10	PBA	97%
* 2	22	5	10	PBA	99%
* 3	28	5	10	PBA	99%
* 4	28	5	10	**FPBA**	99%
* 5	28	5	10	PBA	99%
* 6	28	5	10	PBA	99%

* Number of Mesh Cells and Simulation Time

Sim	Number of Mesh Cells	Simulation Time
* 1	6,554,416	4 hr 36 min
* 2	3,415,100	4 hr 41 min
* 3	5,806,080	3 hr 54 min
* 4	5,806,080	2 hr 36 min
* 5	5,806,080	1 hr 39 min
* 6	5,806,080	3 hr 54 min

Simulation Results

- The following graphs show the plots of the scalar isolation: 20log mag[s21] dB
- Note that the ports within the simulation model are simplified air dielectric and identical.

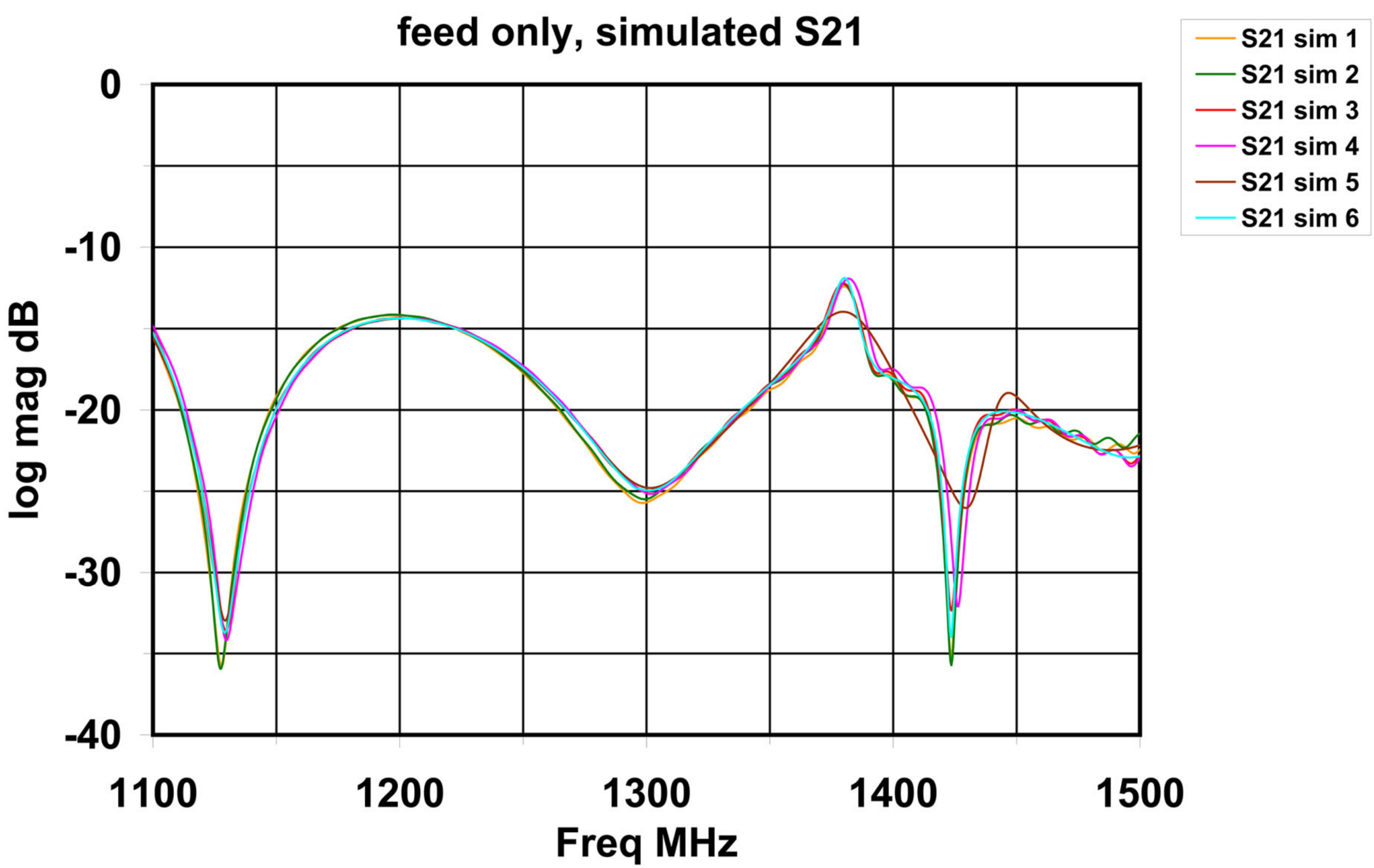


Figure 6: Compare six s21 simulations of the feed

- The application of the AR filter in simulations 5 and 6 smoothed the response curves.
- The use of FPBA in simulation 4 shifted the frequency slightly.

- Next we compare the simulation to the actual measurement data.

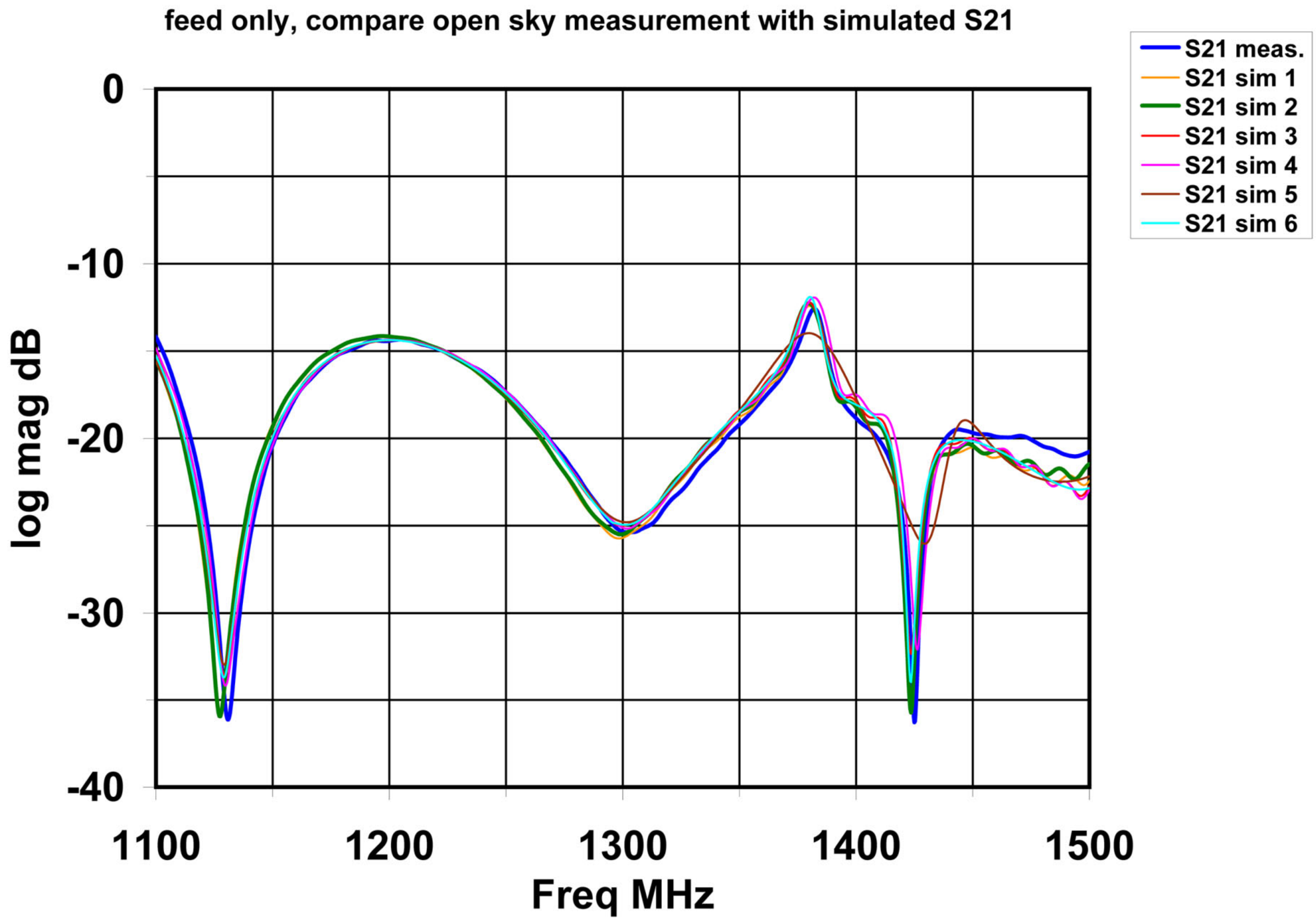


Figure 7: Compare actual measurement data dB[s21] with the simulations

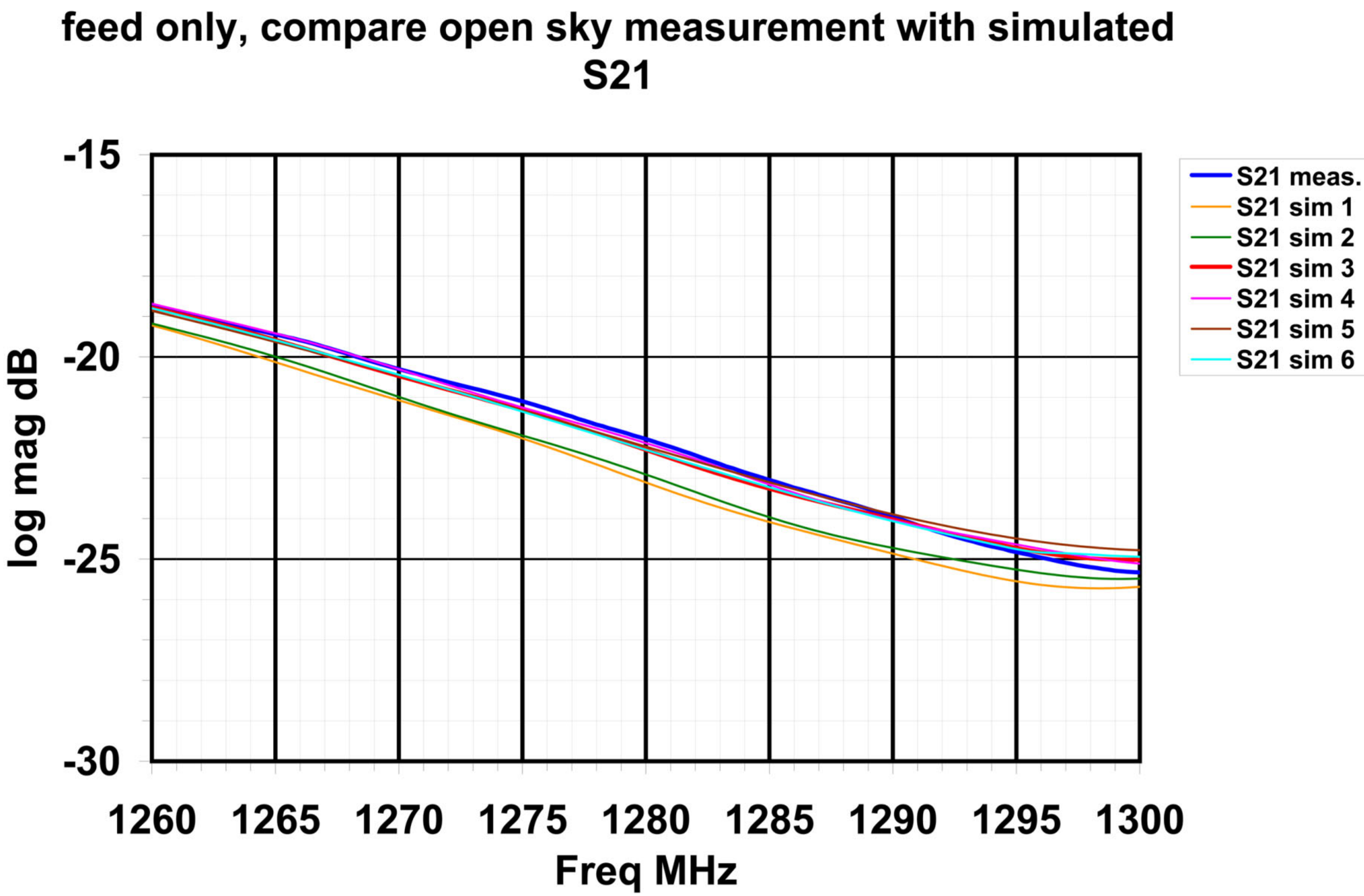


Figure 8: Compare actual measurement data with the simulations over the frequency span of 1260MHz to 1300MHz

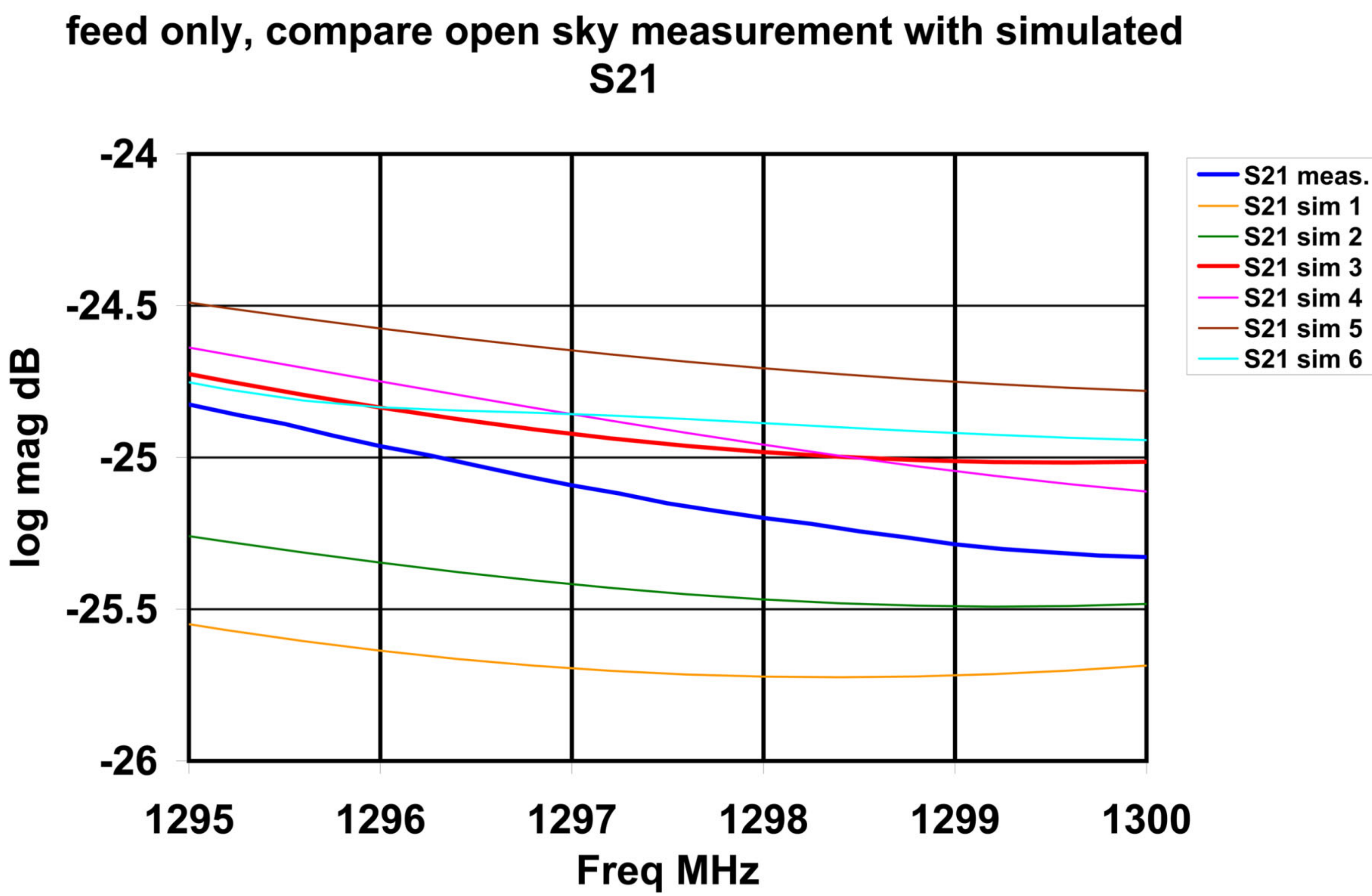


Figure 9: Compare actual measurement data with the simulations over the narrow frequency span of 1295MHz to 1300MHz

Simulation – Measurement Comparison

- The simulations agree with the measurement data within 0.25dB at the frequency of interest, and within less than 1dB over a wider range.
- Keep in mind:
  - The fabrication of the feed has manufacturing tolerances
  - The measurement of the feed required very careful calibration and de-embedding of a pair of 12 foot coaxial cables plus an adapter between N and DIN 7-16

Simulation – Measurement Comparison

- It is useful to set the Transient simulator and Global Mesh Properties to use a minimum of 22 lines per wavelength, PBA meshing, and use 60dB accuracy.
- Increasing the number of lines per wavelength to 28 does not seem to be necessary.

S11 compare 6 simulations

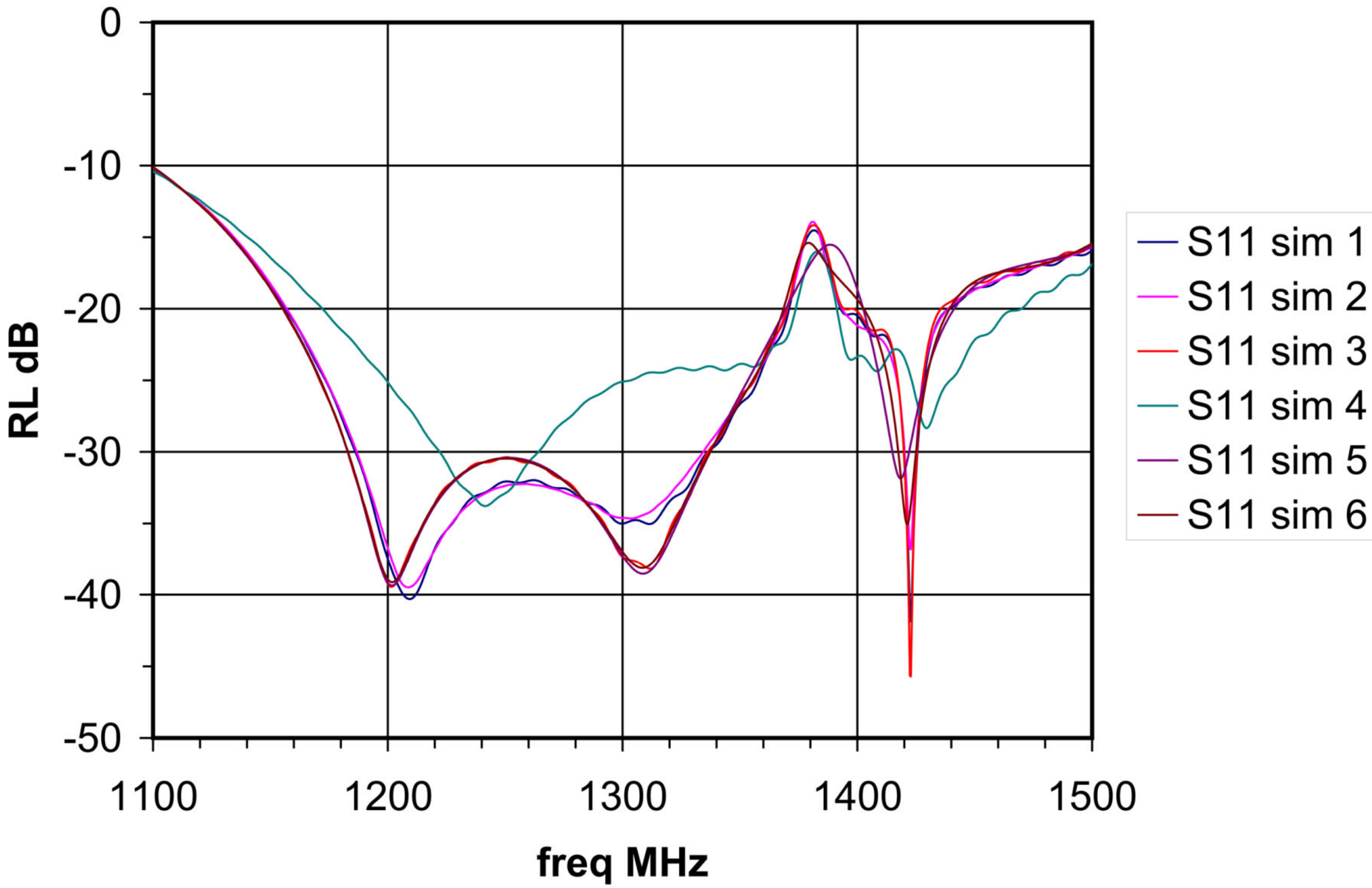


Figure 10: Compare six simulations of the port s11

- Notice some interesting groupings and also differences among the six simulations of the same structure model.
- It shows that the simulation settings make a considerable difference while simulating port match.
- Simulation 4 stands out from the rest and it is the only one with the Global Mesh setting of FPBA.
- According to CST technical support, FPBA is efficient for very complex structures but not for this feed. They were able to make the accuracy of the s11 simulation more closely match the PBA by significantly subgridding and increasing the number of meshcells to 12 million.
- There are two other distinct groupings. Over the range of 1200MHz to 1350MHz, simulations 1 and 2 track each other, and simulations 3, 5, and 6 track.

Important Notes about Measurements

- The actual fabricated feed was measured four separate times.
- Different sets of coaxial cables were used twice, and some measurements had different coaxial adapters.
- There was an expected and noticeable difference in the return loss of s11 and s22
  - Port 1 on the actual feed is a Type N connector
  - Port 2 is a DIN 7-16 connector.
  - The sizes, match, and delay of these connectors are different.

S11 and S22 measured data of actual feed

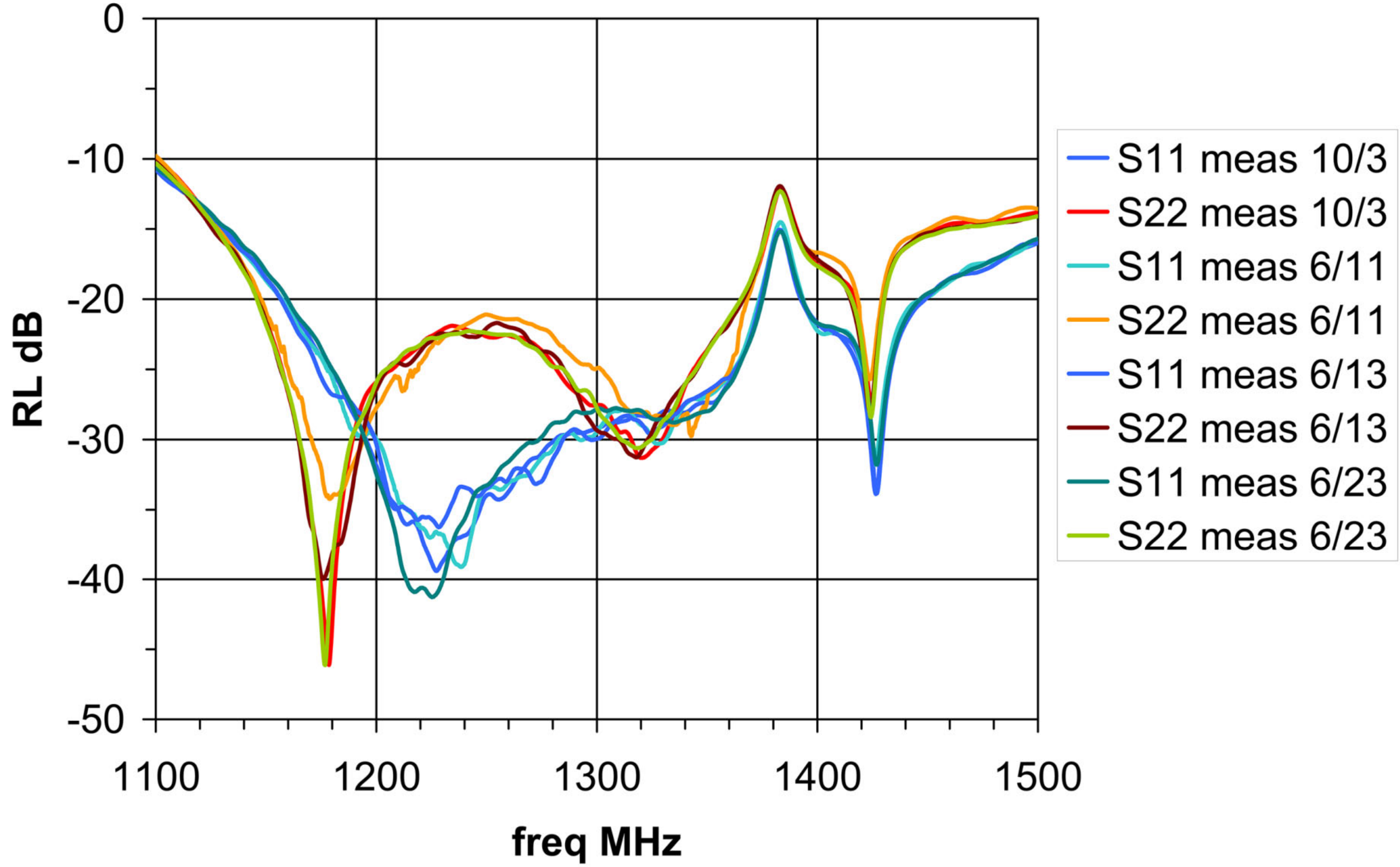


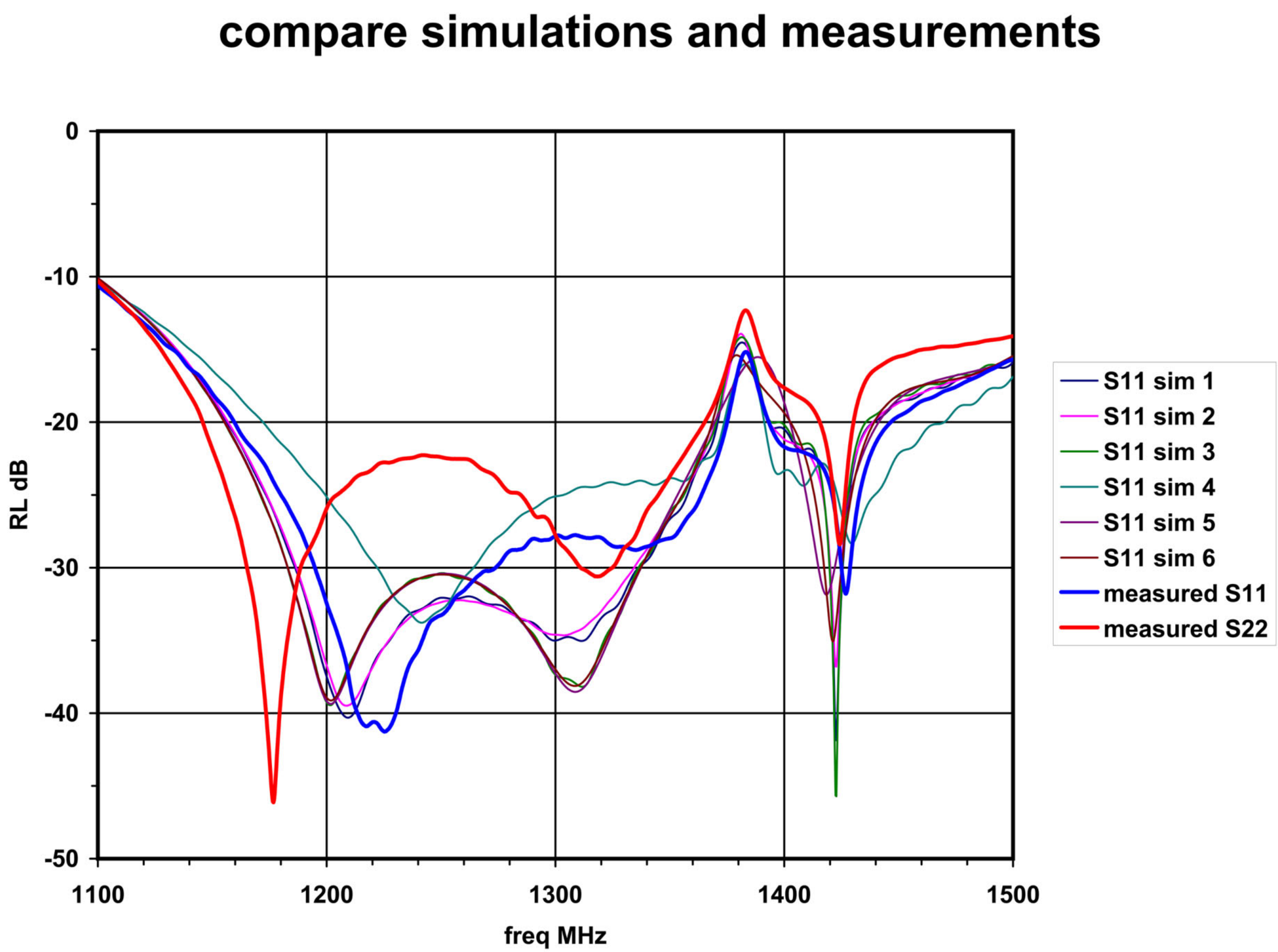
Figure 11: Compare four different measurements of the actual feed

Notes on Measurements continued

- The cables used were Times LMR400UF
  - not metrology cable
  - The ripple is likely imperfections in the cables
- Given that different cables and adapters were used for the different measurements, the data is consistent and shows that the calibration procedure can be trusted.

We will now compare the simulations with the measurements of s11 and s22

Figure 12: Compare six simulations of s11 with actual measurements



New Approach to Analyzing the Data

- Since the test cables were 12 feet long and imperfect, it is not possible to trust measurements approaching -30dB return loss. The inherent loss and mismatch of the cable along with flexing causes unavoidable errors.
- The most significant source of differences is the delay of the connectors.
- Instead of comparing the scalar return loss, the complex s-parameter data from three of the simulations was compared with three of the measurements. Then a small delay was subtracted from the measured s-parameters to correspond to the connectors.

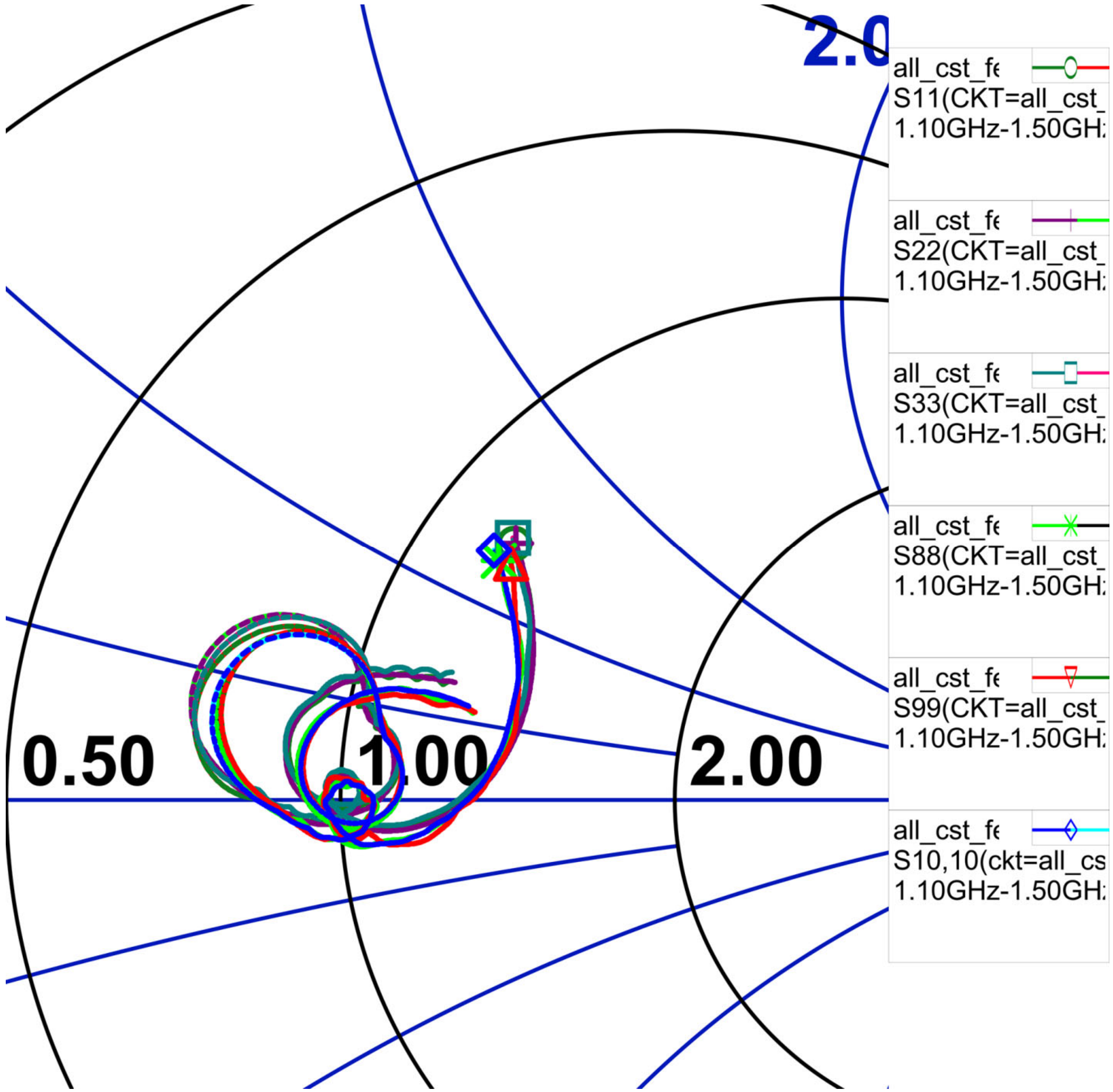


Figure 13: Complex s-parameter comparison of simulated and measured data

Simulations of Feed with Dish

- The only high quality dish of intermediate size available for accomplishing the measurements was 12 feet in diameter. Actual measurements are 357cm and f/d=.375.
- We did not want to begin our simulations with a dish this large because it would take too long to simulate.
- We began by using a hypothetical dish that was 10 lambdas (231.5cm) in diameter and f/d=.35
- 5 simulations with different settings plus an AR filter (six results total)

* Number of Mesh Cells and Simulation Time

Sim	Number of Mesh Cells	Simulation Time
* 1	470,784,600	261 hr 14 min
* 2	247,066,512	36 hr 9 min
* 3	41,896,879	29 hr 47 min
* 4	27,008,825	13 hr 20 min
* 5	35,829,780	28 hr 30 min
* 6	470,784,600	261 hr 3 min

Simulations 1 and 6 meshed the entire volume including the space in front of the dish

Figure 14: Compare six S11 simulations of the feed with 10 lambda dish

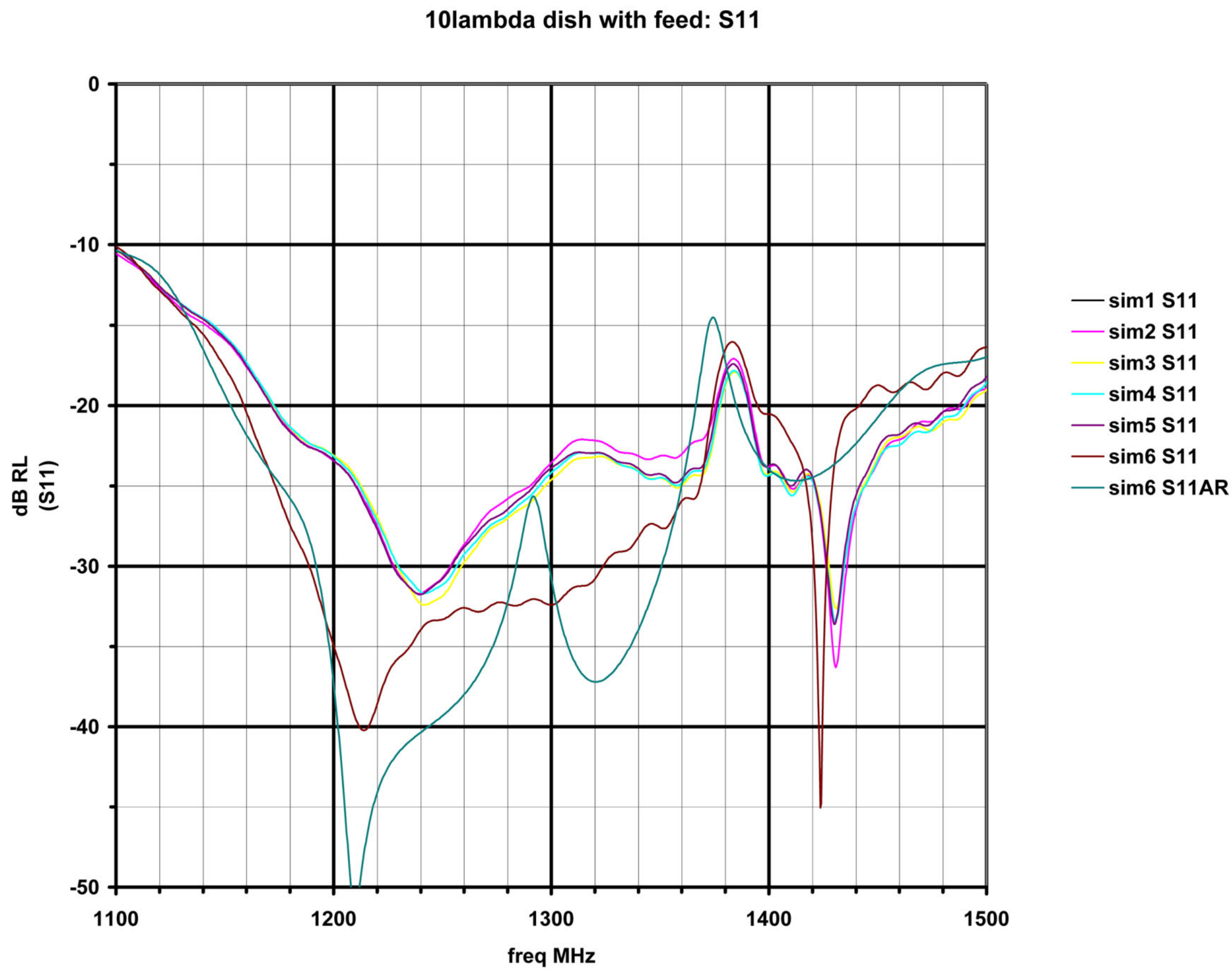


Figure 15: Compare four S11 simulations of the feed with 10 lambda dish

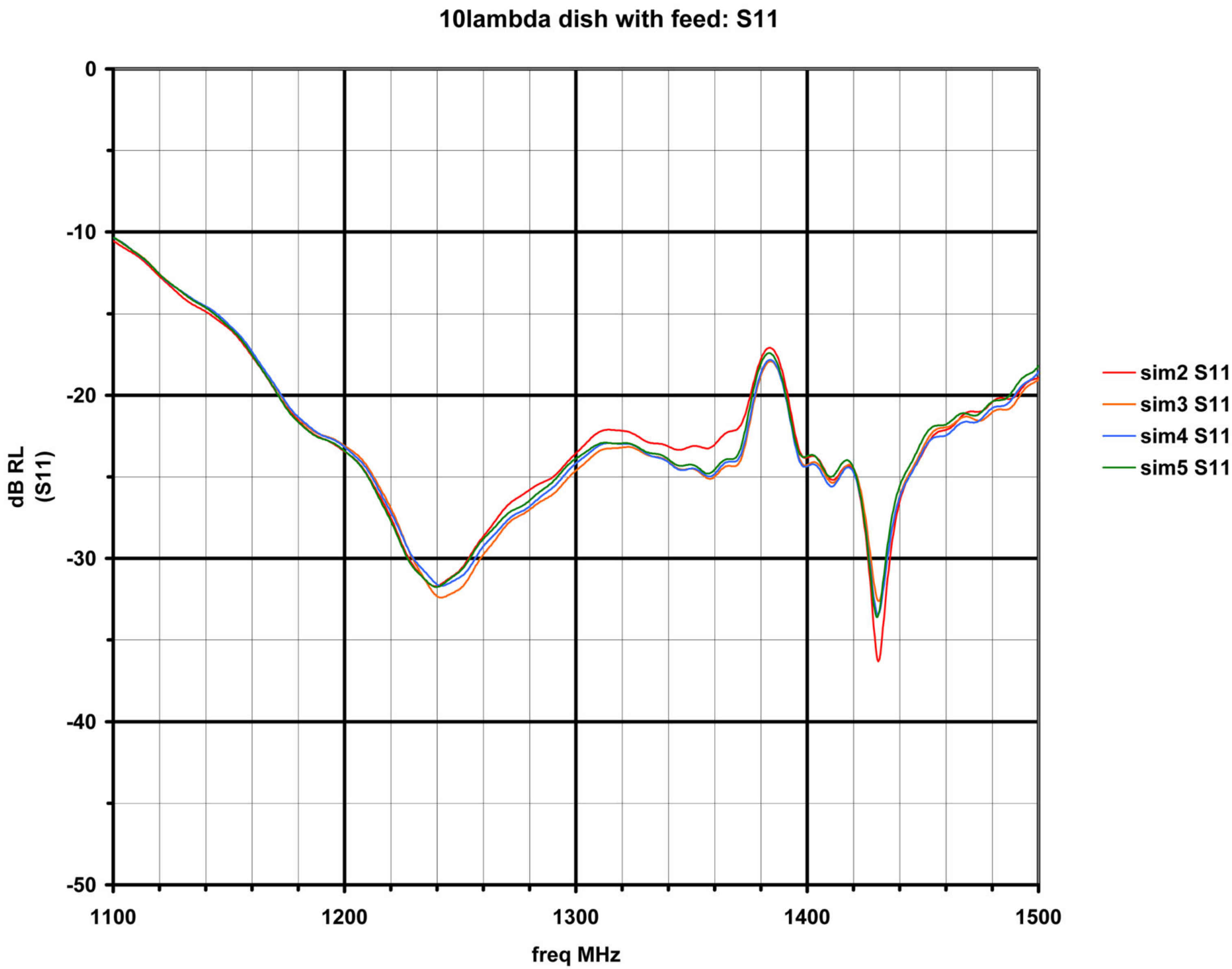
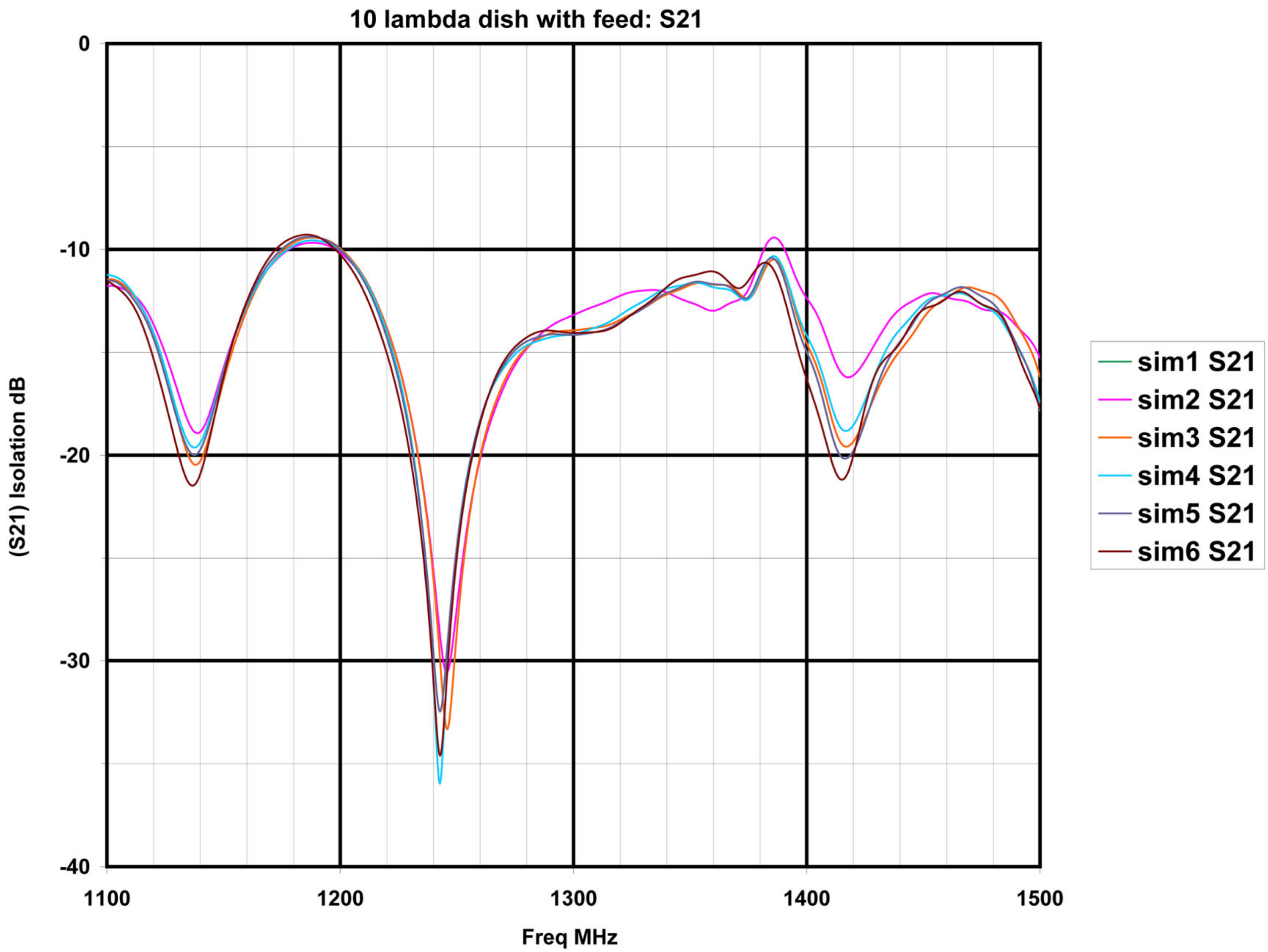


Figure 16: Compare six S21 simulations of the feed with 10 lambda dish



Meshing and Sub-gridding

- Simulations 1 and 6 were identical and finely meshed the entire volume without sub-gridding.
- Simulations 2 and 3 both used the same sub-gridding.
  - A vacuum cylinder was placed around the outside of the entire feed and extended past the opening
  - Another larger vacuum cylinder was placed between the open mouth of the feed and extended all the way to the dish surface.
- Simulations 4 and 5 : further attempt to reduce the simulation size by removing the vacuum cylinder between the feed and the dish.

Simulations 2 and 3

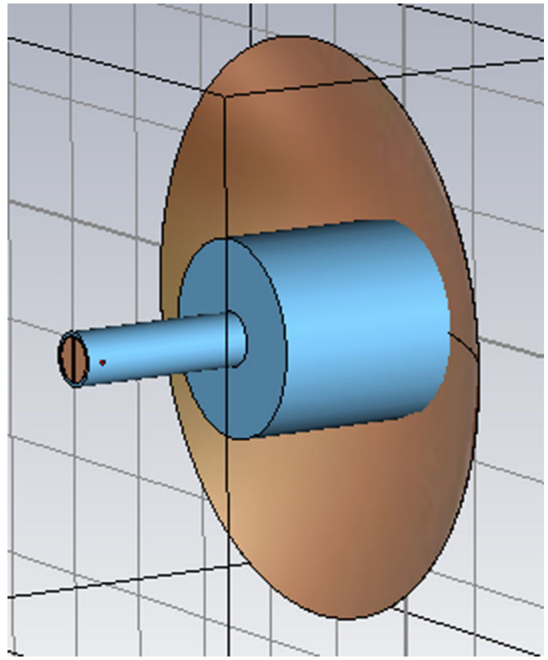
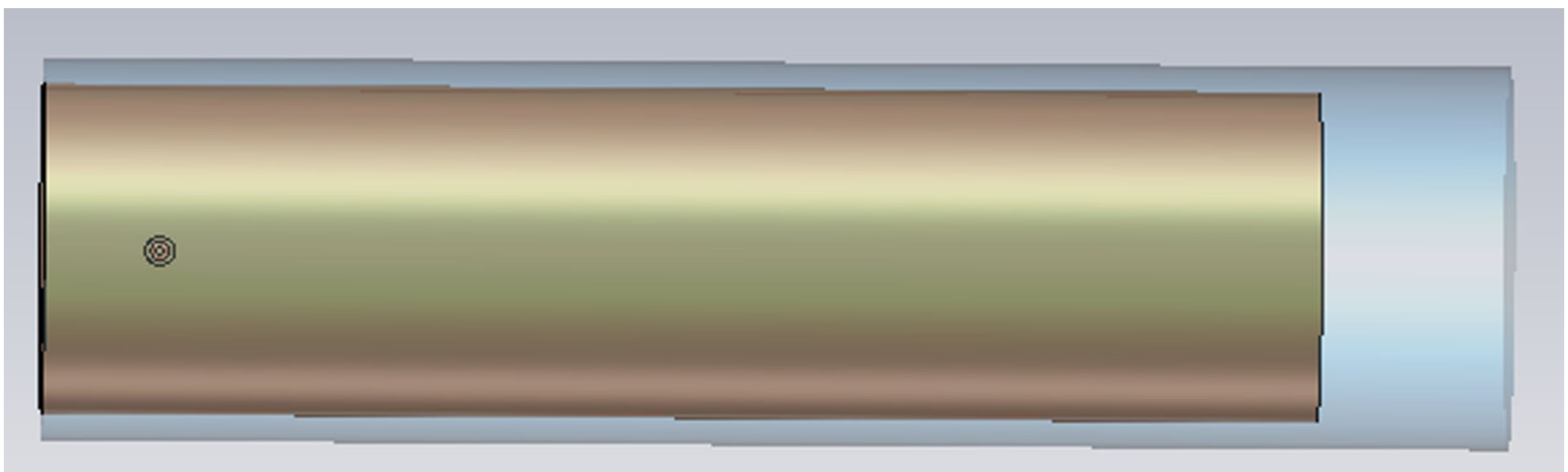


Figure 17

Simulations 4 and 5



* Mesh Settings

Sim	Lines/ wavelength	Lower Mesh Limit	Mesh line ratio	PBA or FPBA	PBA fill limit
* 1	22	5	10	PBA	99%
* 2	14	5	10	automatic	99%
* 3	18	5	10	automatic	99%
* 4	18	5	10	FPBA	99%
* 5	20	5	16	FPBA	99%

* Transient Solver Settings

Sim.	Accuracy	Sub-cycles	Fill limit	PBA timestep	Stability factor	AR filter
* 1	-40dB	4	70	.45	1	no
* 2	-40	4	70	.45	1	no
* 3	-40	4	70	.45	1	no
* 4	-40	4	70	.45	1	no
* 5	-40	4	70	.45	1	no
* 6	-40	4	70	.45	1	yes

Simulation with 12 ft dish

- Initial attempt at simulation of feed with a 12 ft dish using the T solver required more than 500 million mesh cells. Even my computer could not handle that without swapping.
- We simplified the feed ports by assigning waveguide excitation to the two halves of the end of the feed.
- We were now down to a manageable 142 million mesh cells. Simulation time was 48 hrs 13 min.

Figure 18: Simulation of s11 (RL) of the feed with a 12ft dish

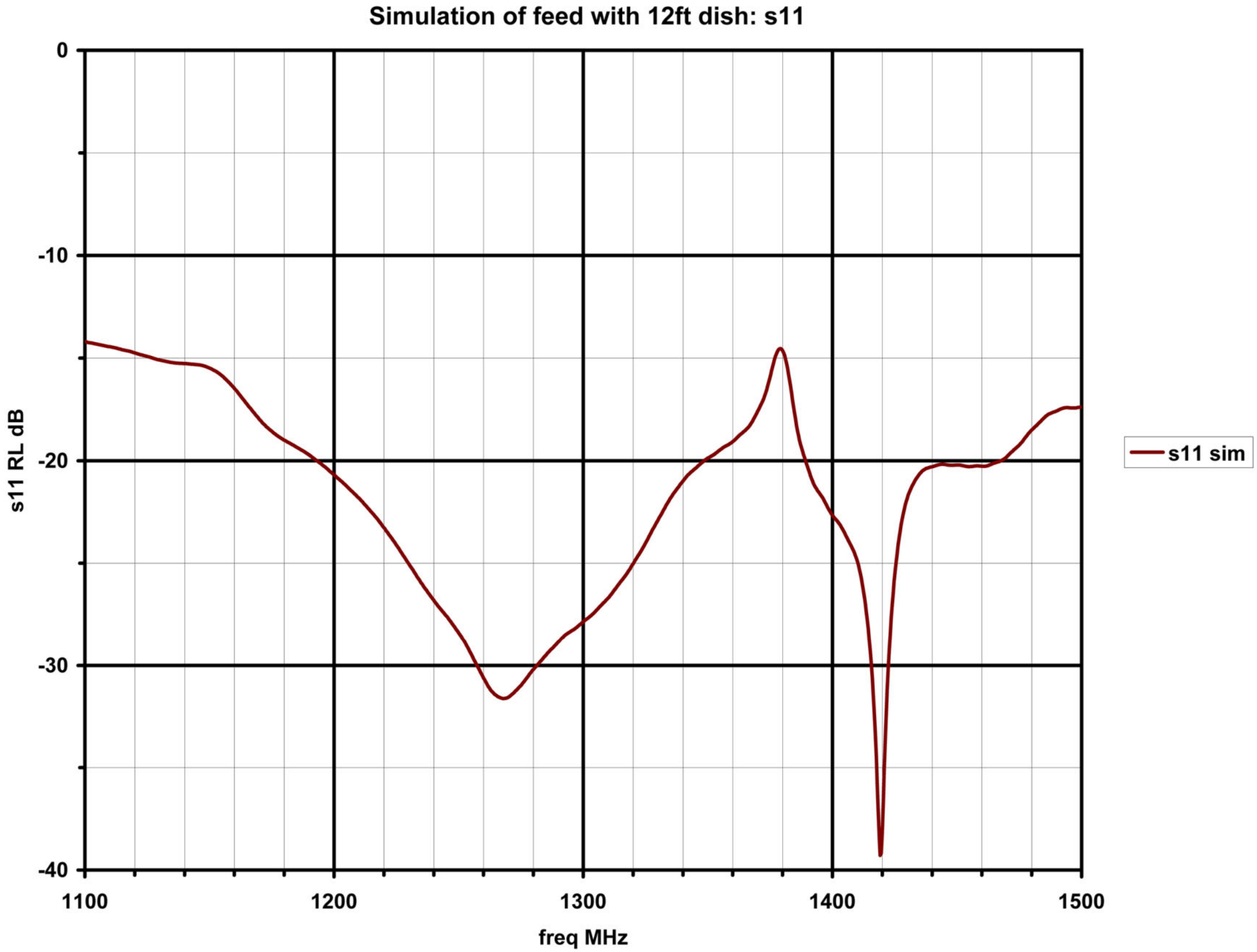
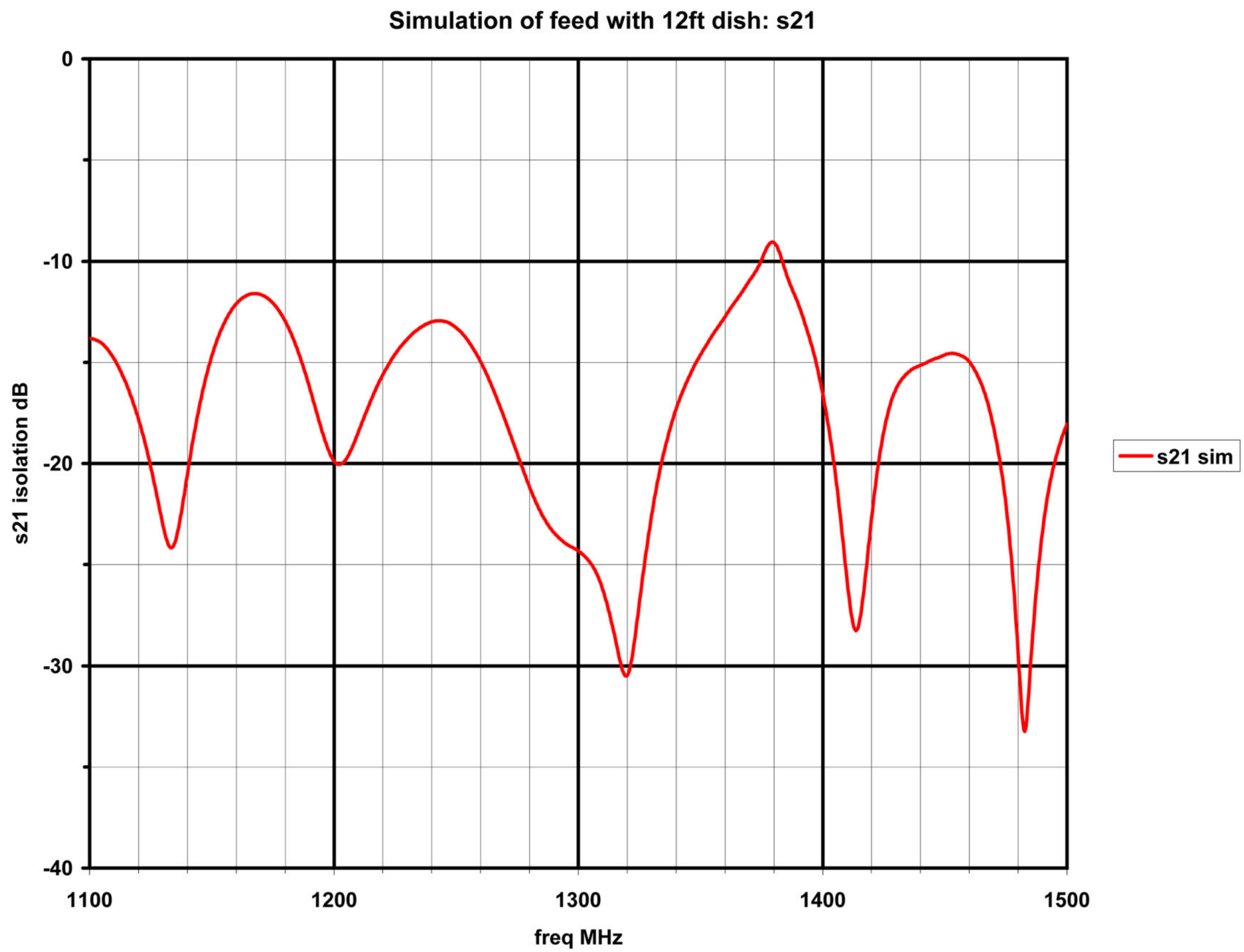


Figure 19: Simulation of s21 (isolation) of the feed with a 12ft dish



Simulation of Feed with 12 ft Dish

- The simulation results shown in Figures 6 and 7 are using the modified feed model with two waveguide ports.
- We will see in the comparison with measured data, the s11 is most accurate at the design center frequency and the S21 is accurate over the entire range.
- The setup for actual measurement is shown next. This involved building a feed support.

Figure 20: Construction of the feed support structure

Figure 21: Feed supported above the dish

Measuring Feed to Vertex Distance

- Flexible cloth measuring tape hung from feed for measurement of distance.
- The feed was moved up and down in fine increments from 50 inches to 55 inches.
- Since the prime focus of the dish was calculated to be around 52.7 inches, the finest steps were done around that distance.
- Distance could only be estimated – tape was 6 ft from edge of dish.

Measurement Methods

- The data from the calibrated vector network analyzer was downloaded directly into Excel on a notebook computer via a GPIB interface bus.
- The measurements were impartial and equivalent to a double-blind test
- All four s-parameters were measured at each distance from the vertex of the dish.

Notes on Measurement Equipment

Vector Network Analyzer:	Agilent 8753ES
Type N calibration kit:	HP85054A
Type DIN (7-16) calibration kit:	Maury 2750F
Type N precision adapters:	Maury 8801K
initial type DIN 7-16 to N adapters:	Andrew (male and female)
later type DIN 7-16 to N adapters:	Rosenberger 60S153-K50N1
	Rosenberger RT53S160-K50
	Suhner (male and female)
	Maury 2706C

Figure 22: Measured s11 of the feed with an actual 12 foot dish at various distances from the vertex

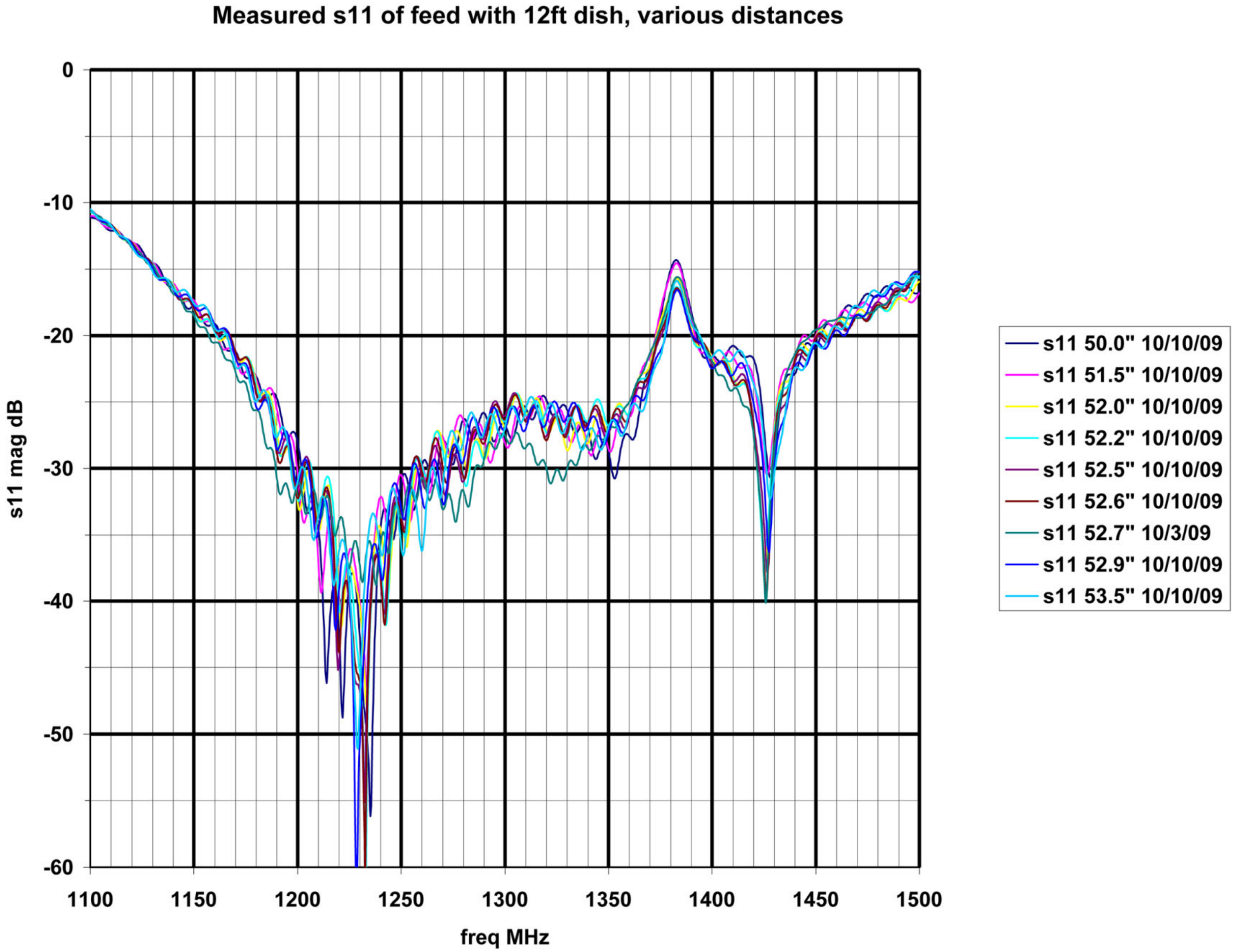
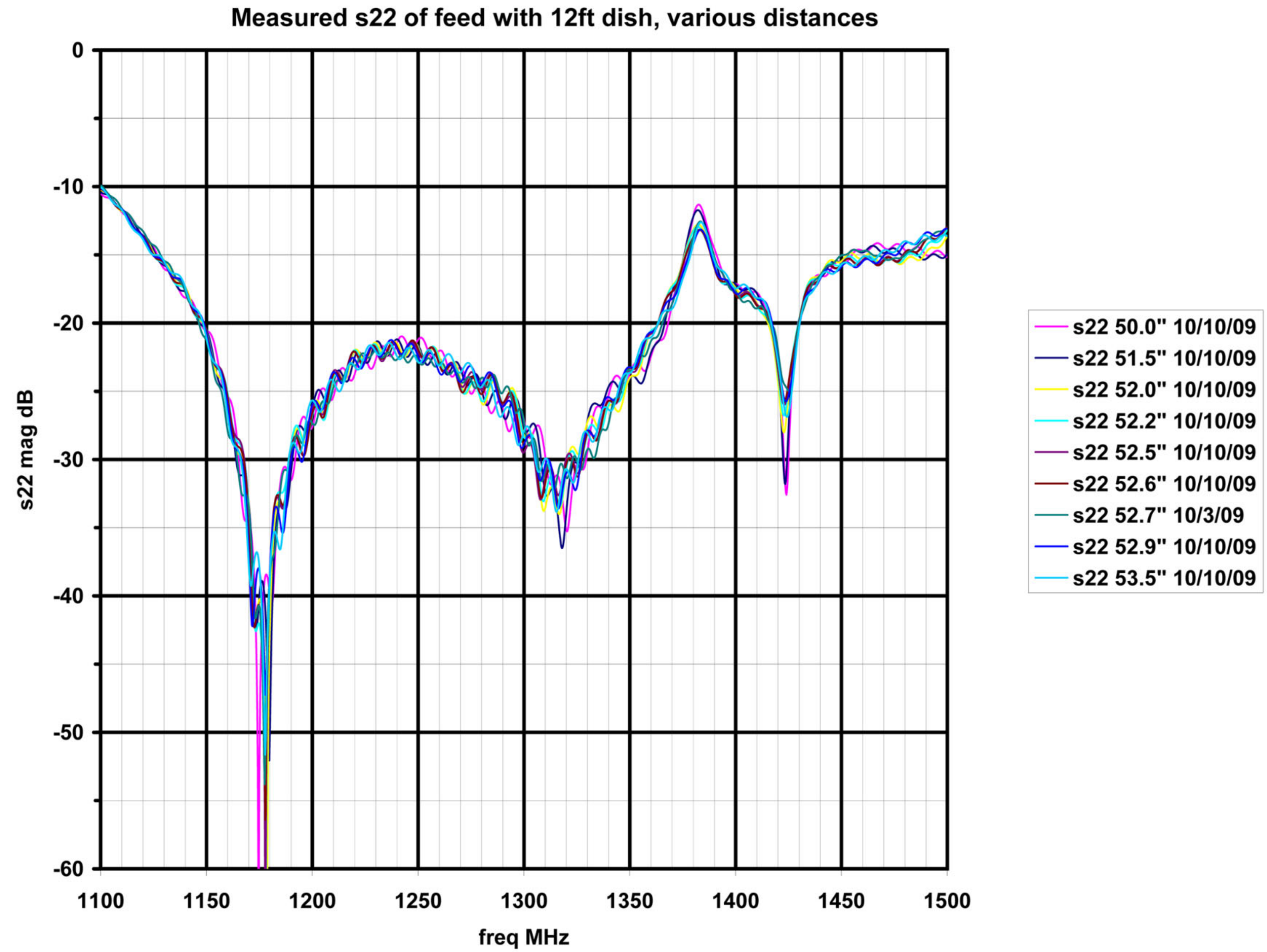


Figure 23: Measured s22 of the feed with an actual 12 foot dish at various distances from the vertex



Notes about Modified Port

- Since we are comparing waveguide ports to coaxial ports, the s11 and s22 simulations were only accurate at the design center frequency of the septum which is 1296MHz.
- The s21 simulation was accurate over the entire frequency range.

Figure 24: Measured s11 of the feed with an actual 12 foot dish at various distances from the vertex, compared with simulation

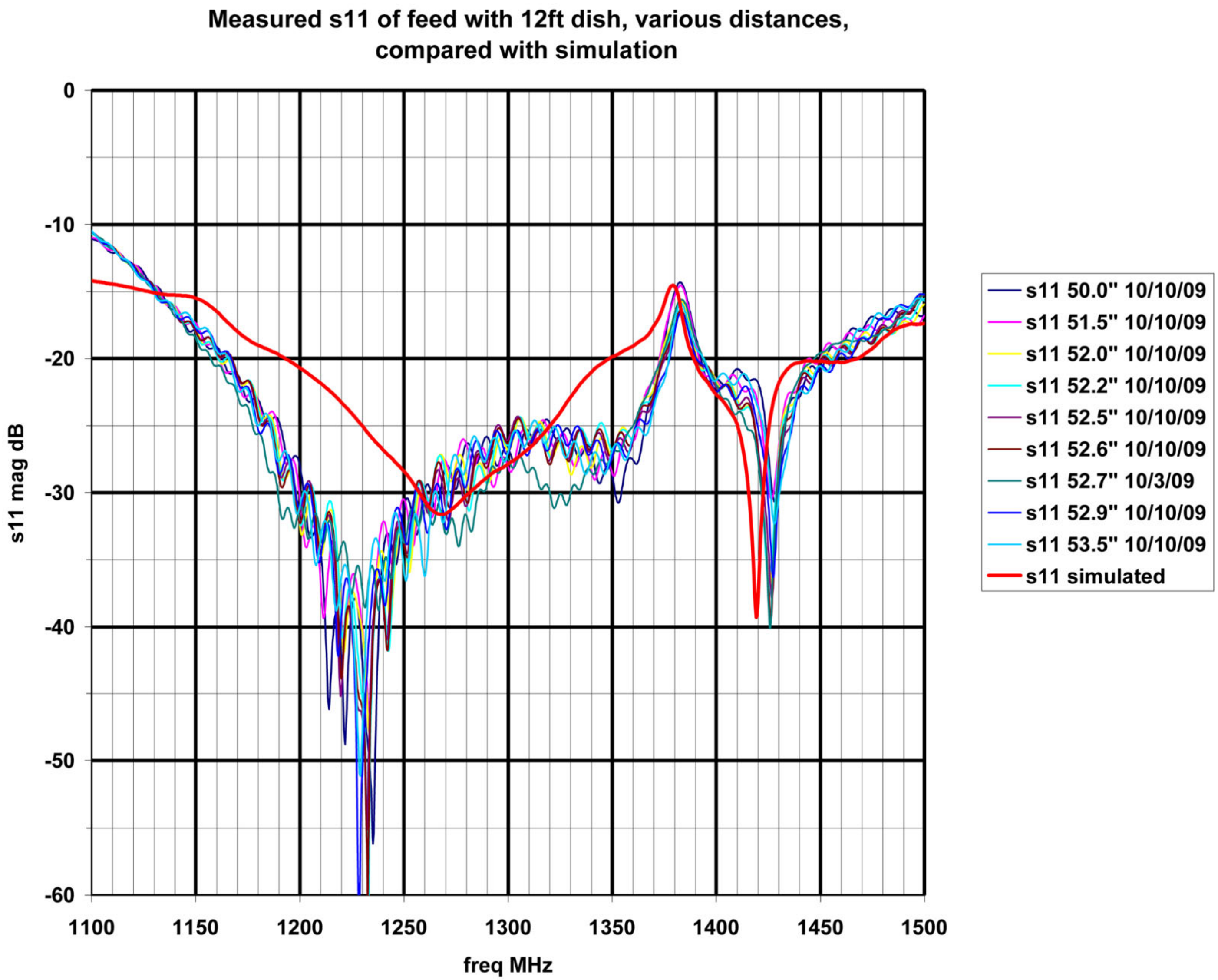


Figure 25: Measured s22 of the feed with an actual 12 foot dish at various distances from the vertex, compared with simulation

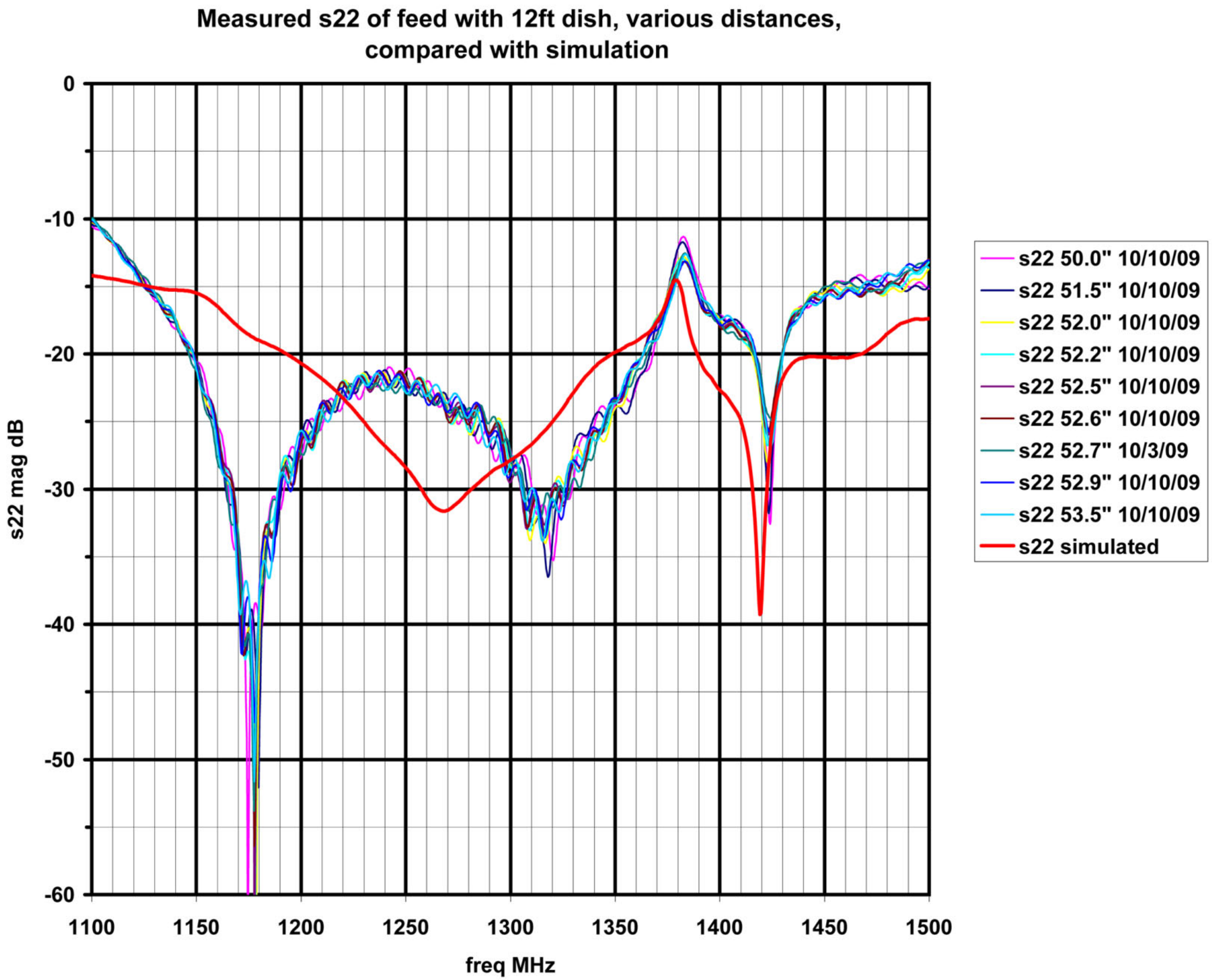


Figure 26: Measured s11 of the feed with an actual 12 foot dish at various distances from the vertex, compared with measurement of the feed pointed at open sky

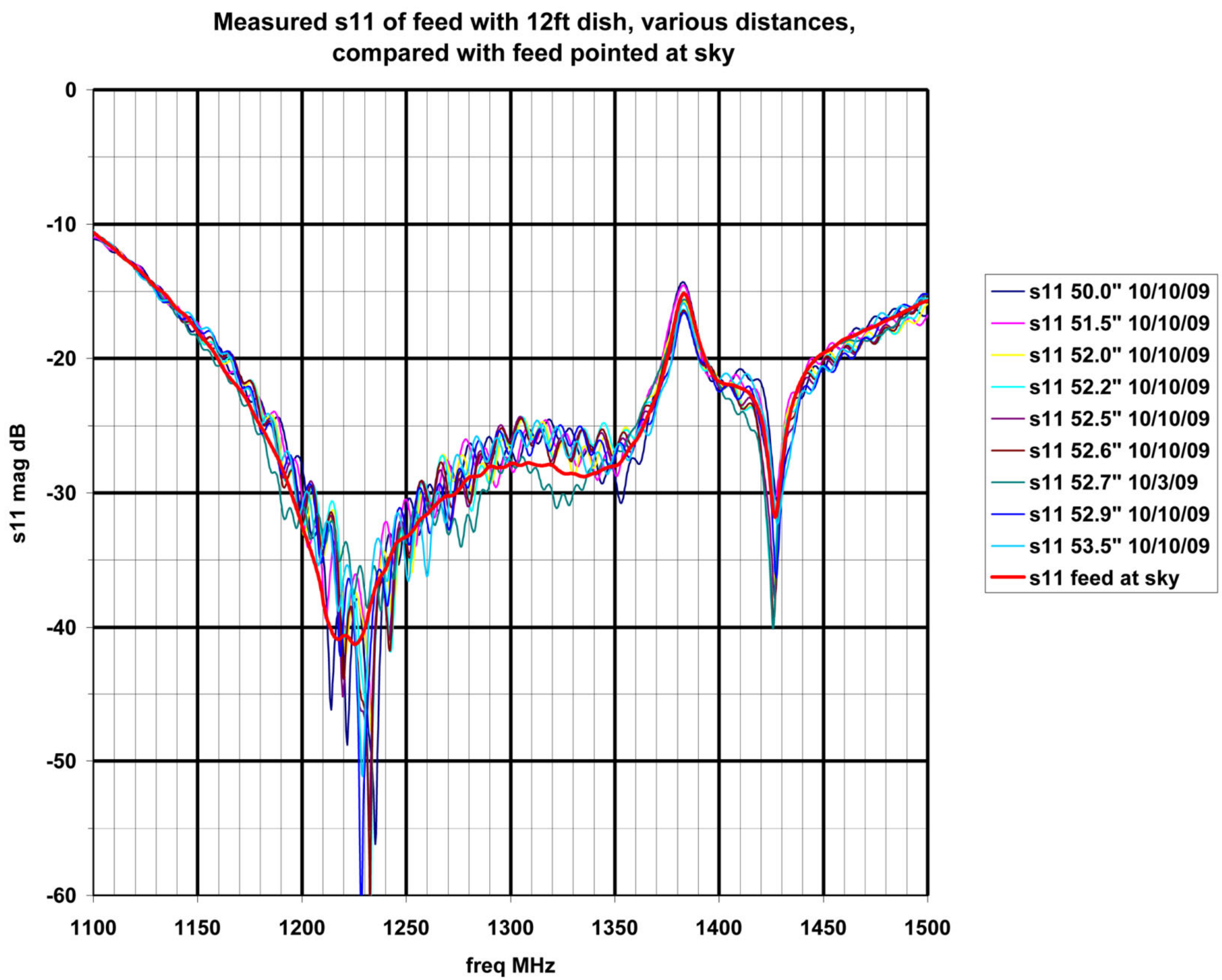


Figure 27: Measured s22 of the feed with an actual 12 foot dish at various distances from the vertex, compared with measurement of the feed pointed at open sky

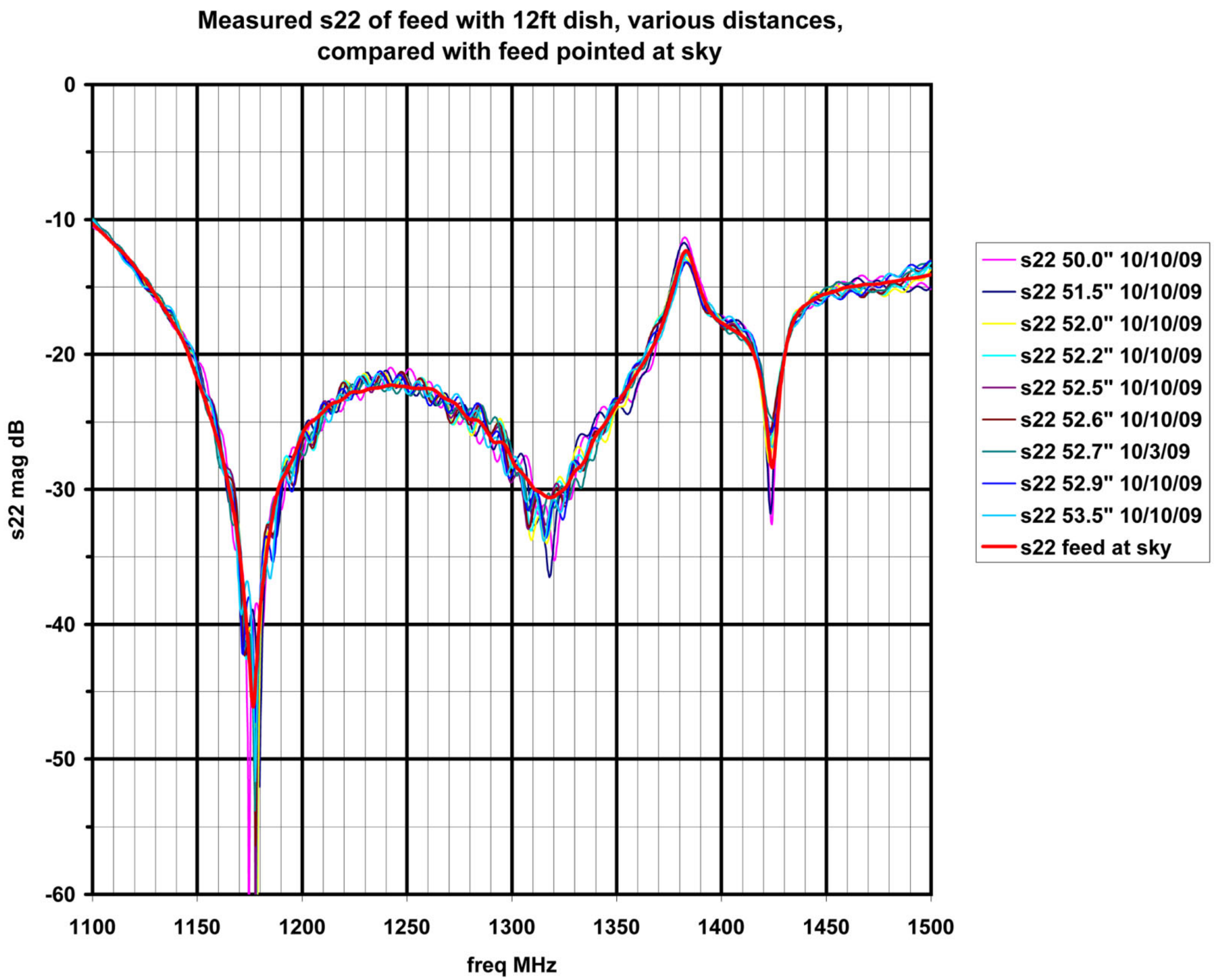


Figure 28: Measured s21 of the feed with an actual 12 foot dish at various distances from the vertex

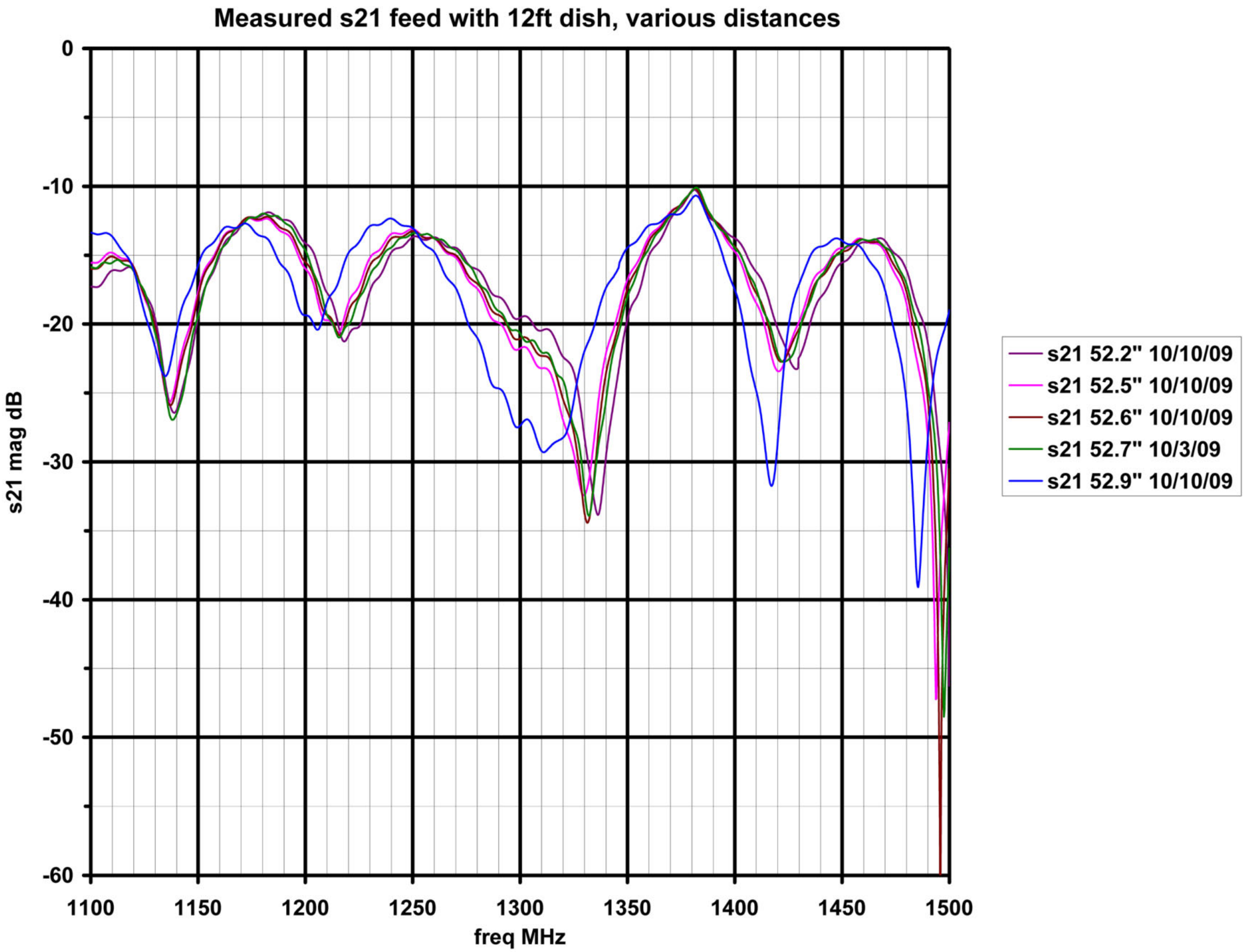


Figure 29: Measured s21 of the feed with an actual 12 foot dish at various distances from the vertex, compared with the simulation

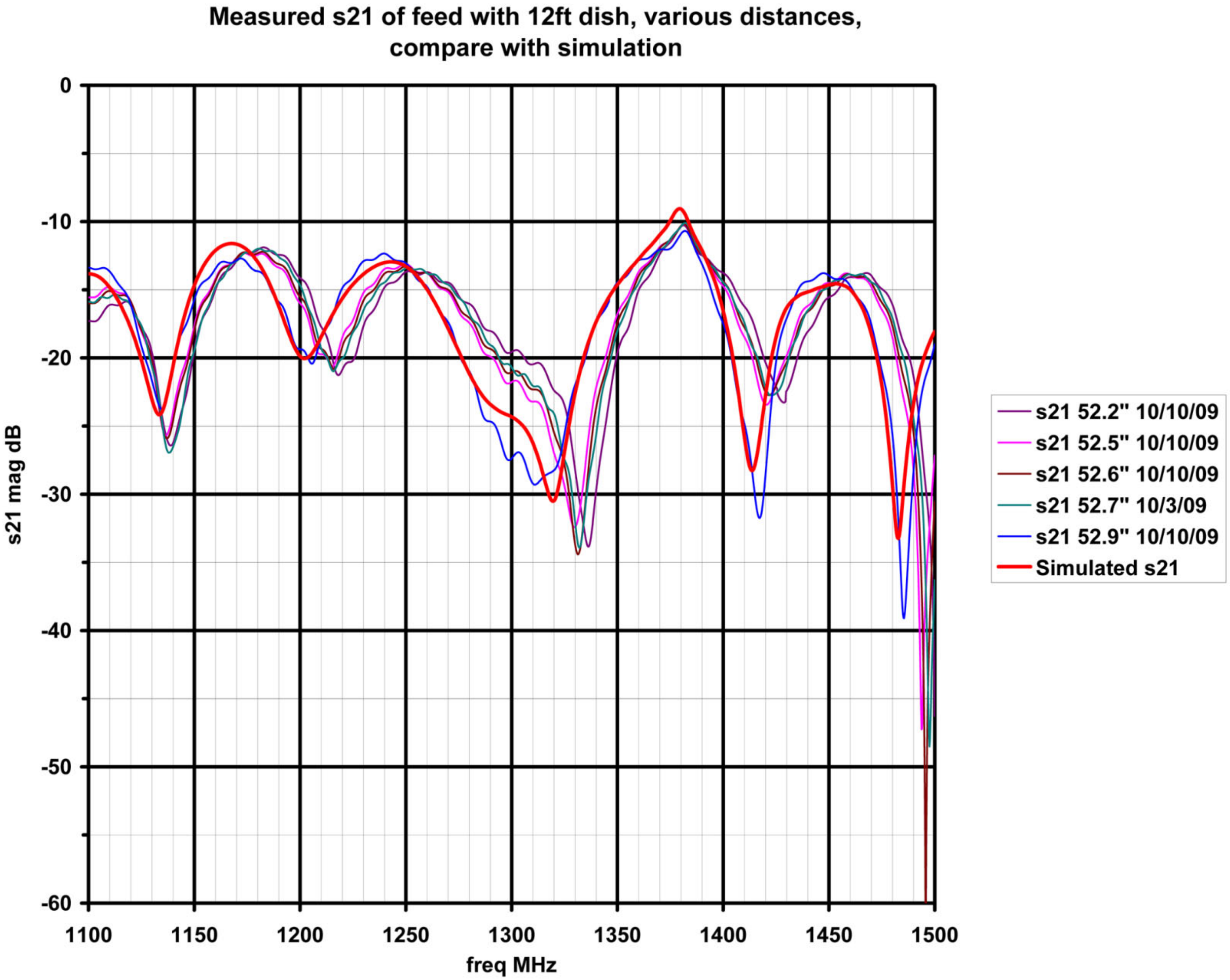
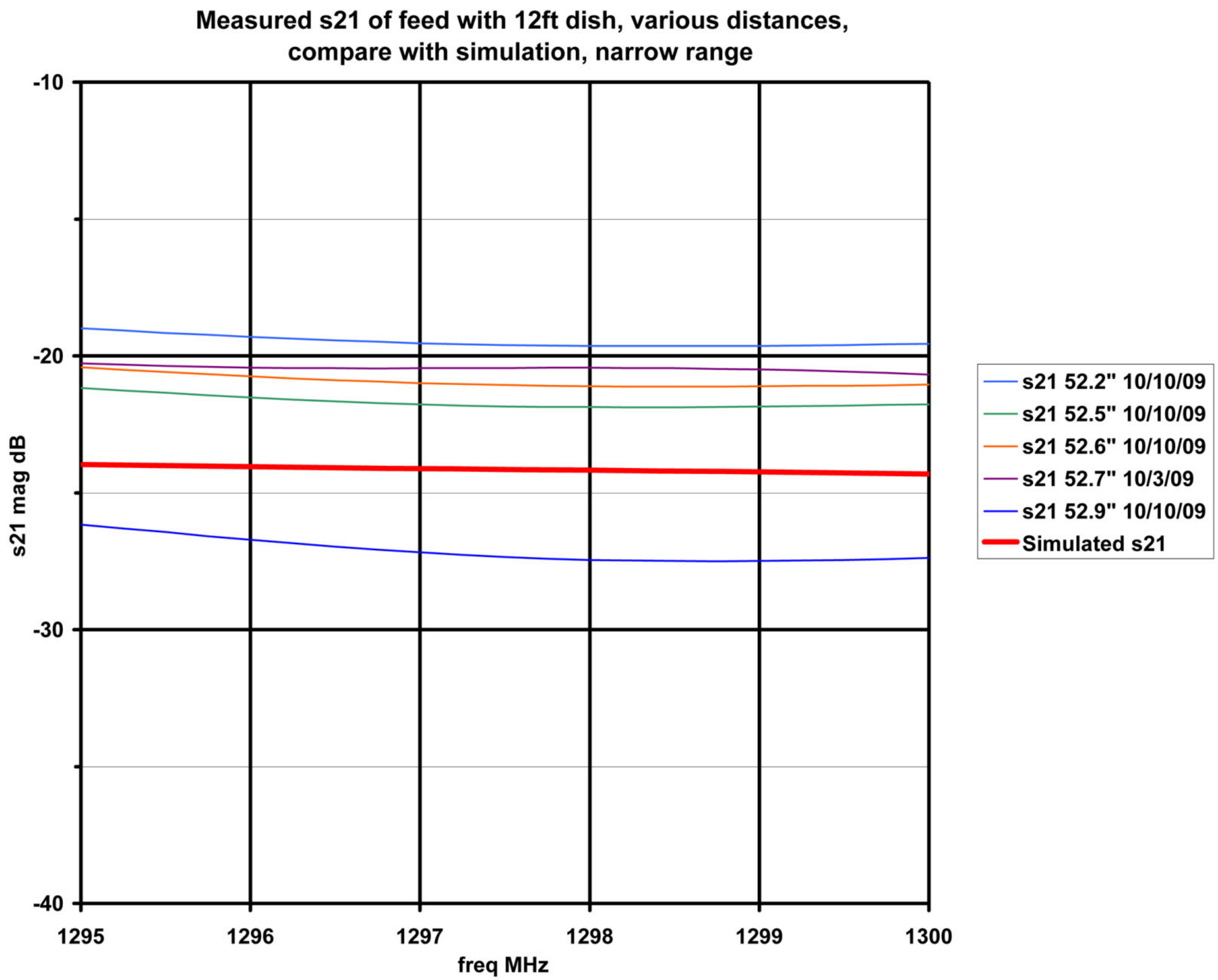


Figure 30: Measured s21, compared with the simulation, narrow frequency range



Reflections from Dish back into Feed

- The center of a prime focus dish always reflects energy back into the feed
- First described by Silver in Rad Lab vol 12
- Effect on match and isolation
- Can be mitigated; but is it necessary?

Figure 31: s21 of feed pointed at open sky compared to feed pointed at dish

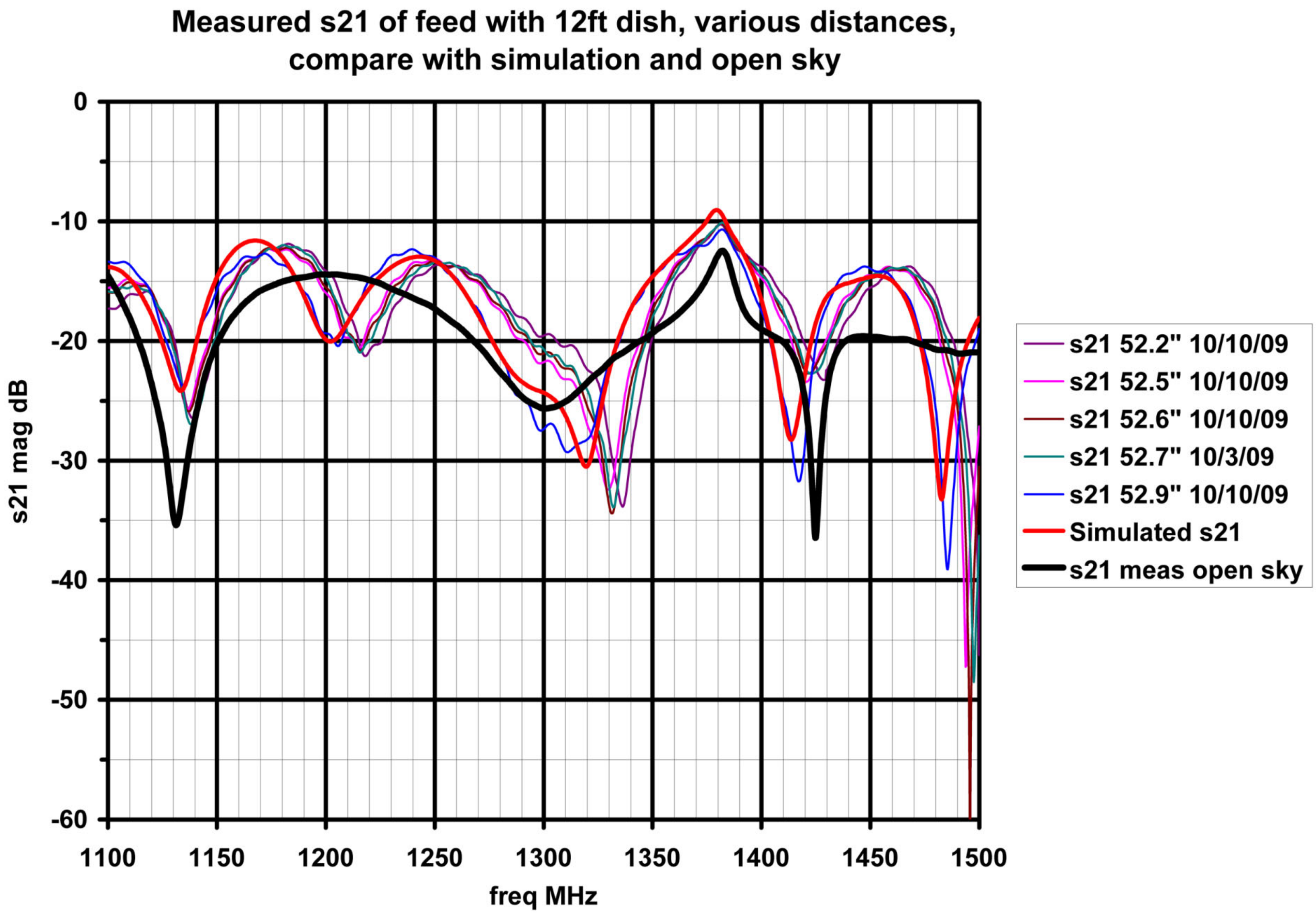
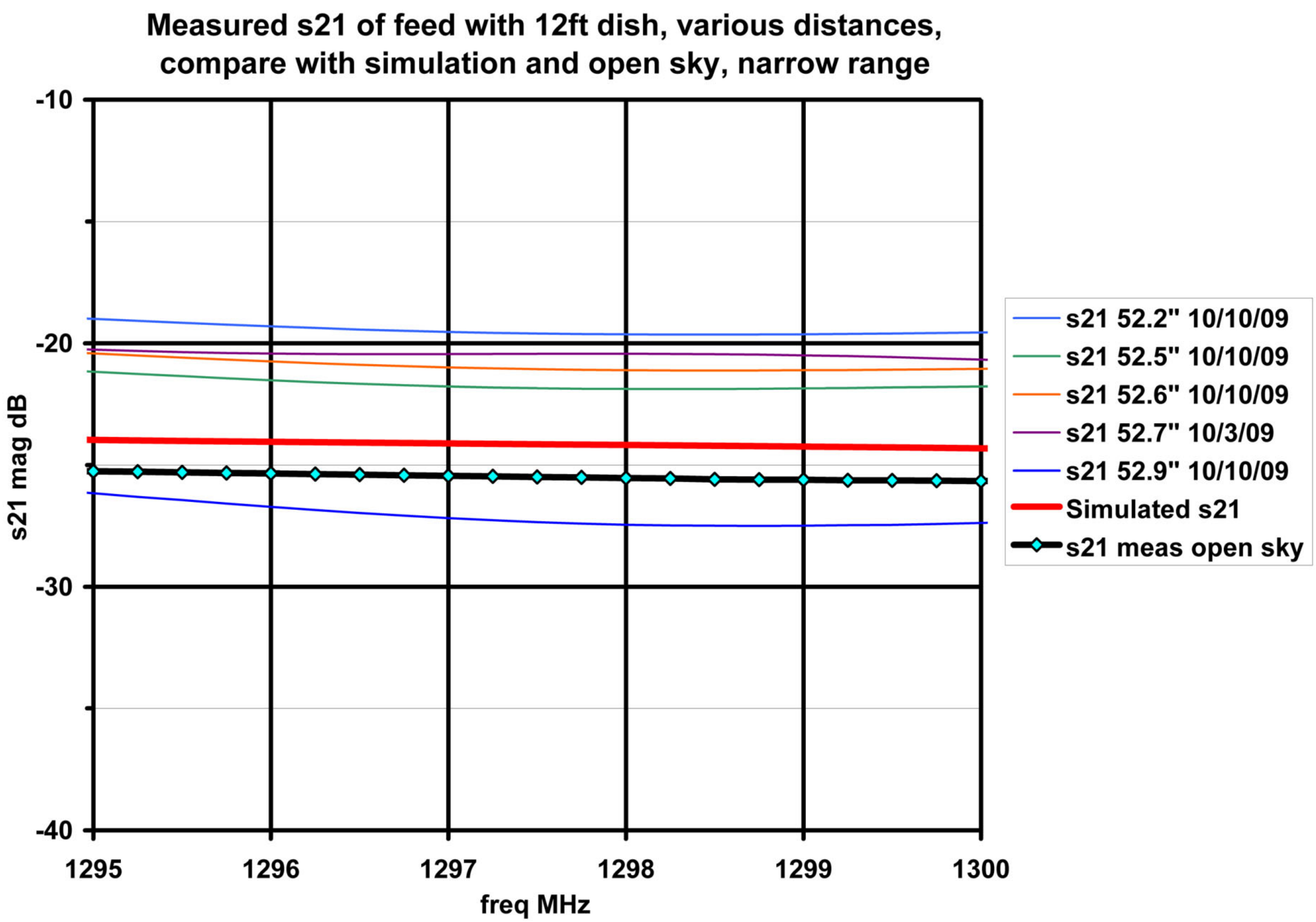


Figure 32: Narrow range view of s21 comparison



Measurement Issues

- Full two-port SOLT calibration of VNA done through the test cables
- Problem of disparate connectors:
  usual cal is done with same connector types on both ports. This required N and DIN.
- Many recent VNAs can combine matrices of two different full two-port cal sets
- Then add in the series adapter
- Port delay is not conveyed with GPIB data

Acknowledgement for the assistance of the following people

1. Temporary non-reflective feed support design and construction by Jim Moss (N9JIM)
2. Assistance with measurements by Paul Zander, senior member IEEE SCV AP-S (AA6PZ)

JEFFREY PAWLAN (IEEE M 1989, SM 1996) has been a consultant as owner of Pawlan Communications for 18 years. Prior to that, he had worked for many companies in California in very diverse areas of analog, RF, and microwave design. Some of his work was for NASA projects. He also taught engineering part-time. Born and raised in the Los Angeles area, he attended UCLA and several other universities. He enjoyed learning many different fields and has 13 years of higher education including a Doctorate degree. Jeffrey took an uncommon interest in microwave engineering at a young age and built his first dish feed for operation on 23cm in 1961. By 1962 he was building 10GHz receivers and transmitters and he attended his first MTT Symposium exhibition in Los Angeles.

He is a member of MTT and UFFC and is currently on the IEEE SCV Section ExCom Board.

Rastislav GALUŠČÁK, Ing., was born in 1959, in Martin, Slovakia. From 1978 to 1983 he studied radio-electronic engineering at the Technical University in Košice, Czechoslovakia. He worked several years at a radio-telecommunication company as technician and later as a design engineer. Mr. Galuščák is a Ph.D. student at the Czech Technical University - Prague in the Electromagnetics Dept. His interests are dish antennas, special antenna feeds and EME communication.

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