Description and Laboratory Evaluation of a Prototype LMR Multiband Antenna System

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Contents

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1 Introduction

This report documents laboratory evaluation of a prototype land mobile radio (LMR) multiband antenna system. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [1]. In [2], we presented our "Phase I" design concept for this antenna system. The system architecture is shown in Figure 1. Components of this system have been designed and evaluated separately, as documented in the following reports already released:

- The design of the antenna itself is documented in [2], and a hardware implementation and laboratory evaluation is documented in [3]. The efficacy of the proposed stub tuning scheme was also demonstrated in [3].
- The design and laboratory evaluation of the stubline tuner is documented in [4].
- The design and laboratory evaluation of the RF power detection circuits is documented in [5].
- The design and laboratory evaluation of the 700/800 MHz bandpass filter channel is documented in [6].
- The design and laboratory evaluation of the circuit board containing the other four bandpass filter channels is documented in [7].

These reports are appended to the end of this report.

The construction of the "laboratory evaluation" version of the Phase I antenna system has been completed, and is shown in Figures 2 – 4. In this report, we describe the elements of the design that have not already been documented, and describe measurements of this system in the laboratory.

2 Design

The various component printed circuit boards described in [4]–[7] have been mounted to a aluminum 1U 19-in rack tray. The tray also serves as the antenna's ground plane. The antenna jack is a panel mount connector which is type SMA on the "board" side and type N on the antenna side. The tray is mounted upside down (with respect to the way it would normally be used, in a rack), such that the circuit boards face down, underneath the ground plane.

The radio side of the stubline tuner is connected to a Mini-Circuits ZEDC-10-2B coupler using a 12 cm section of RG-58 coaxial cable.

This implementation uses a Microchip PN DM164120-2 "PICkit 2 44-Pin Demo Board" as its controller. The microcontroller on this board is the Microchip PIC16F887, and the board requires about 20 mA at +5 VDC. The outputs of the power detector circuits are connected to analog-to-digital converter (A/D) inputs on the PIC16F887. Software running on the microcontroller continuously monitors the A/Ds and compares levels to determine if the radio is transmitting and, if so, in which band. Digital logic outputs are connected in pairs to the relay coil terminals on the stubline tuner (neither side of the coil is grounded). When a relay state change is required, one of the two outputs is pulsed high while holding the other low.

3 Performance

Figures 5, 6, and 7 show s_{21}, s_{11}, and s_{22} for the system. In each case, the signal path includes the stubline tuner (all relays open), the coupler, and the coaxial cable connecting the two. s_{21} is seen to vary between 1 dB and about 2.5 dB. The coupler's rated insertion loss is between 1.3 dB and 1.8 dB; thus the stubline tuner and the coupler have a roughly equal impact on the system insertion loss. On the antenna side, the in-band reflected power (s_{11}) is found to range between −16.7 dB

and −6.8 dB. (It should be noted that this particular measurement does not have much relevance to system performance since the antenna is very different from a 50 Ω standard termination.) On the radio side, the worst-case in-band VSWR (derived from s_{22}) is 2.0:1.

Figures 8 shows the reflection from the radio-side jack when no stubs are set (i.e., all relays open) and the antenna is connected. Figures 9 and 10 show the same measurement when stubs are set in response to detected transmissions at 144 MHz and 432 MHz, respectively. Note that the stubs considerably improve the performance at the indicated frequencies. Keeping in mind that reflection below about −10 dB corresponds to VSWR better than 2:1, we see that the tuner is able to tune the antenna to an acceptable level of performance.

Also of interest is the sensitivity of the tuner to the transmit power level from the radio. To determine this, an RF signal of 1 W was applied to the radio side of the tuner, and the voltage at the power detector outputs was measured. At 144 MHz, the VHF-H detector read 0.12 V and all other detectors read 0.00 V. At 222 MHz, the 220 MHz detector read 0.02 V and all other detectors read 0.00 V. At 432 MHz, the UHF detector read 0.43 V and all other detectors read 0.00 V. No usable response could be obtained from the VHF-L (25–50 MHz) detector; it appears this is due to the poor performance of the filter bank when the channels are combined. The 700/800 MHz sensitivity was not checked. The level of performance of the VHF-H, 220 MHz, and UHF filter band + detection circuits is usable, but very poor compared to what is expected. This is believed to be due again to the poor performance of the filter bank channels when combined into a single circuit.

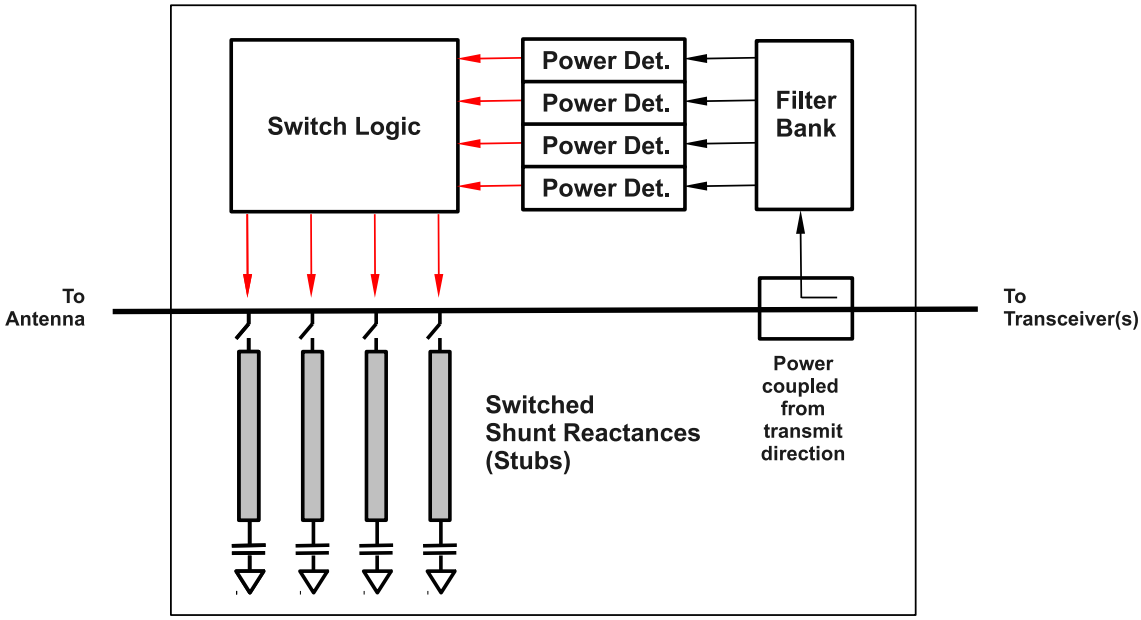

Figure 1: System architecture.

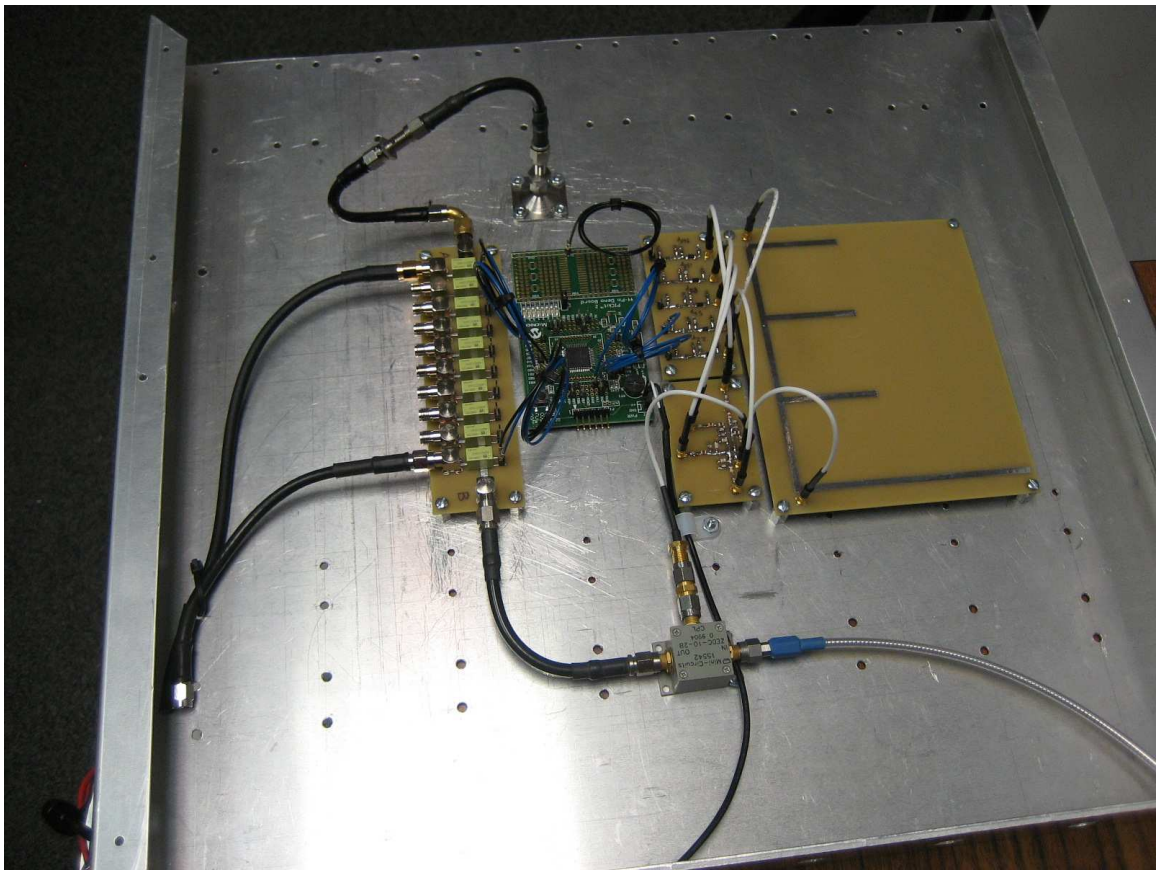

Figure 2: The laboratory evaluation version of the system, showing the primary system components.

Figure 3: The laboratory evaluation version of the system, mounted for testing (view from underneath).

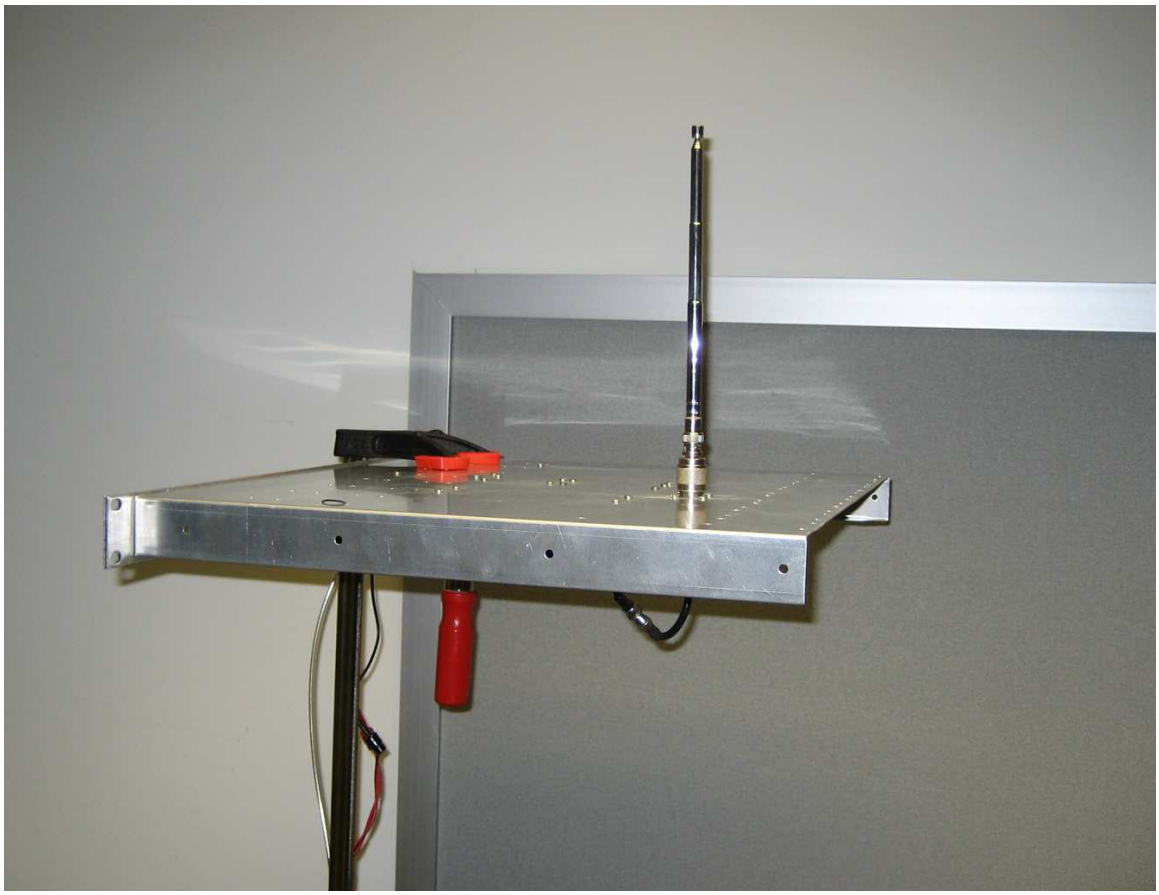

Figure 4: The laboratory evaluation version of the system, mounted for testing (view from above).

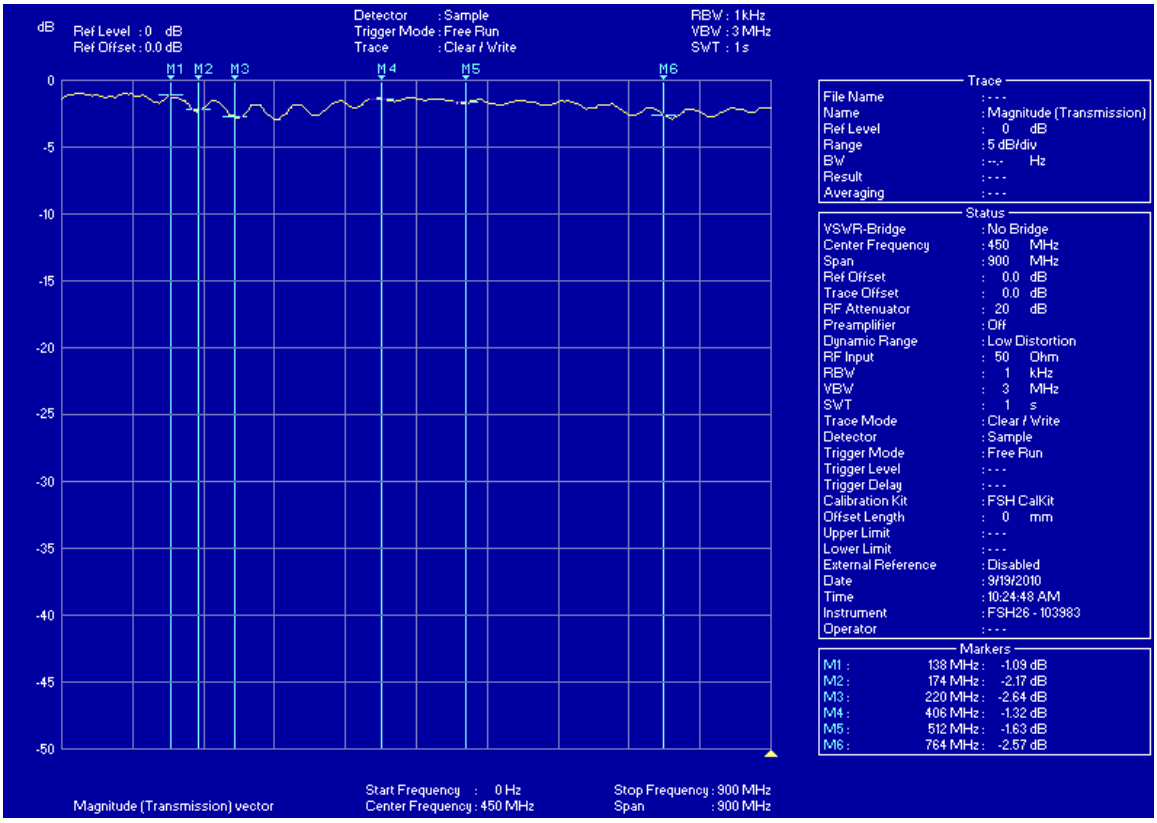

Figure 5: s_{21} through antenna tuner, all relays open.

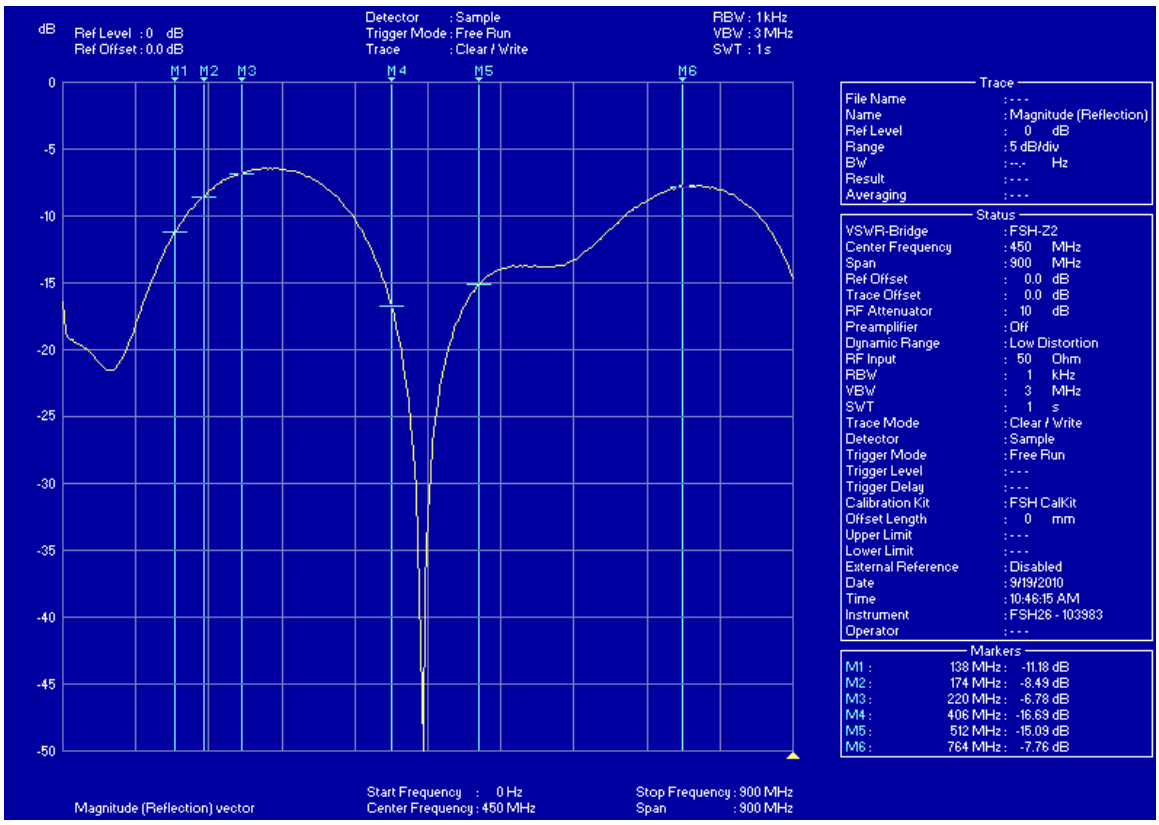

Figure 6: s_{11} looking into antenna tuner antenna jack, all relays open.

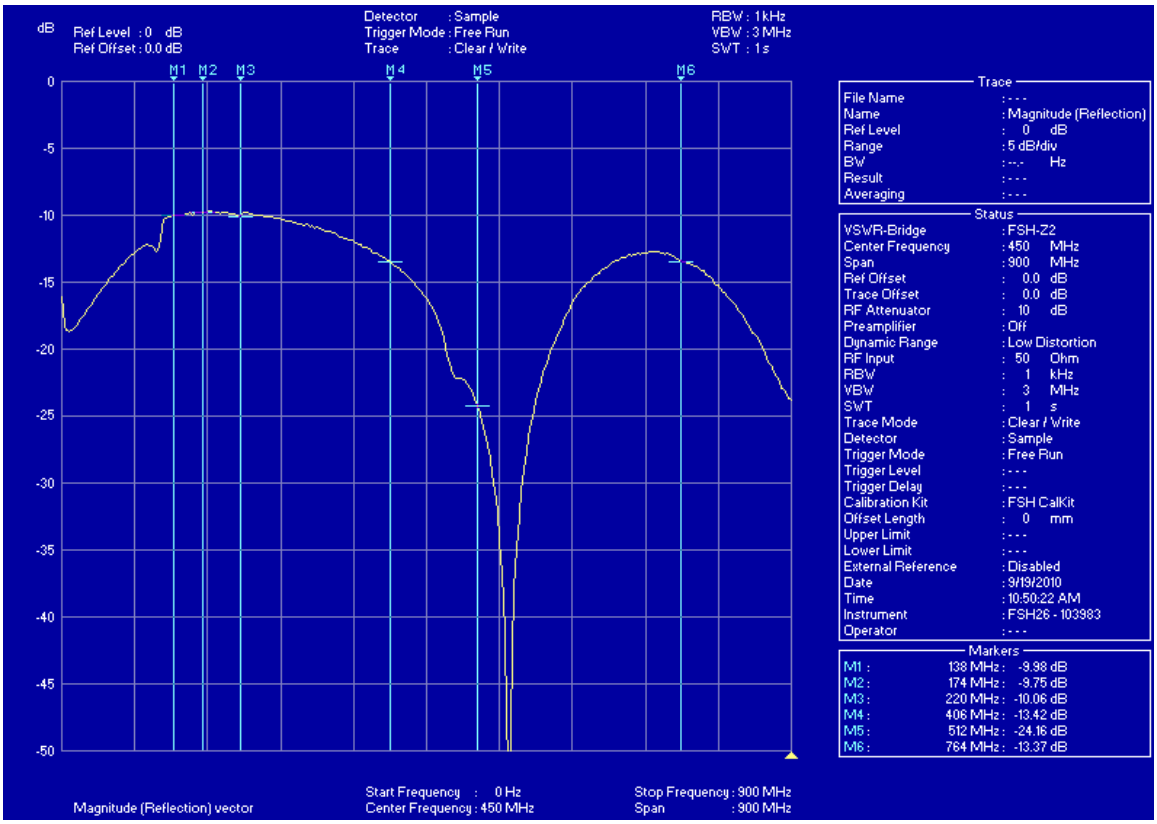

Figure 7: s_{22} looking into antenna tuner radio jack, all relays open. (Antenna jack terminated into 50Ω.)

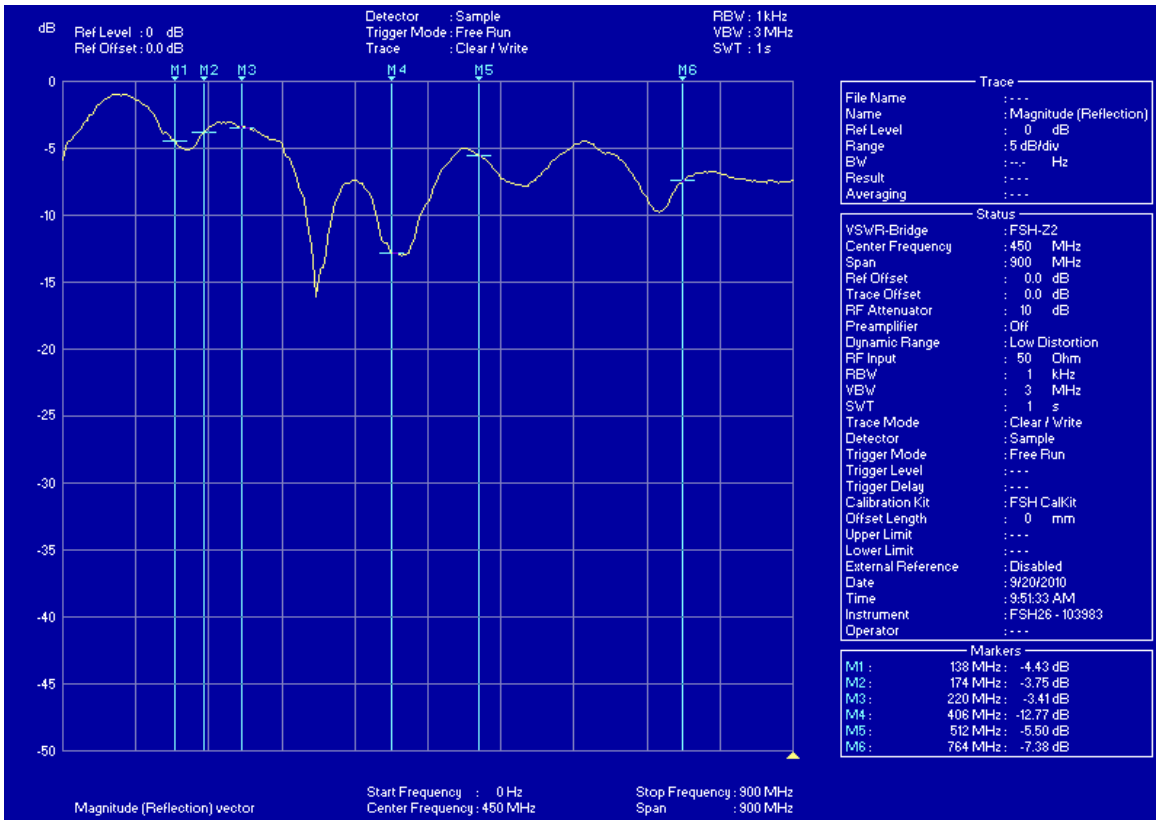

Figure 8: Reflection coefficient looking into antenna tuner radio jack, all relays open. (Antenna jack terminated into antenna.)

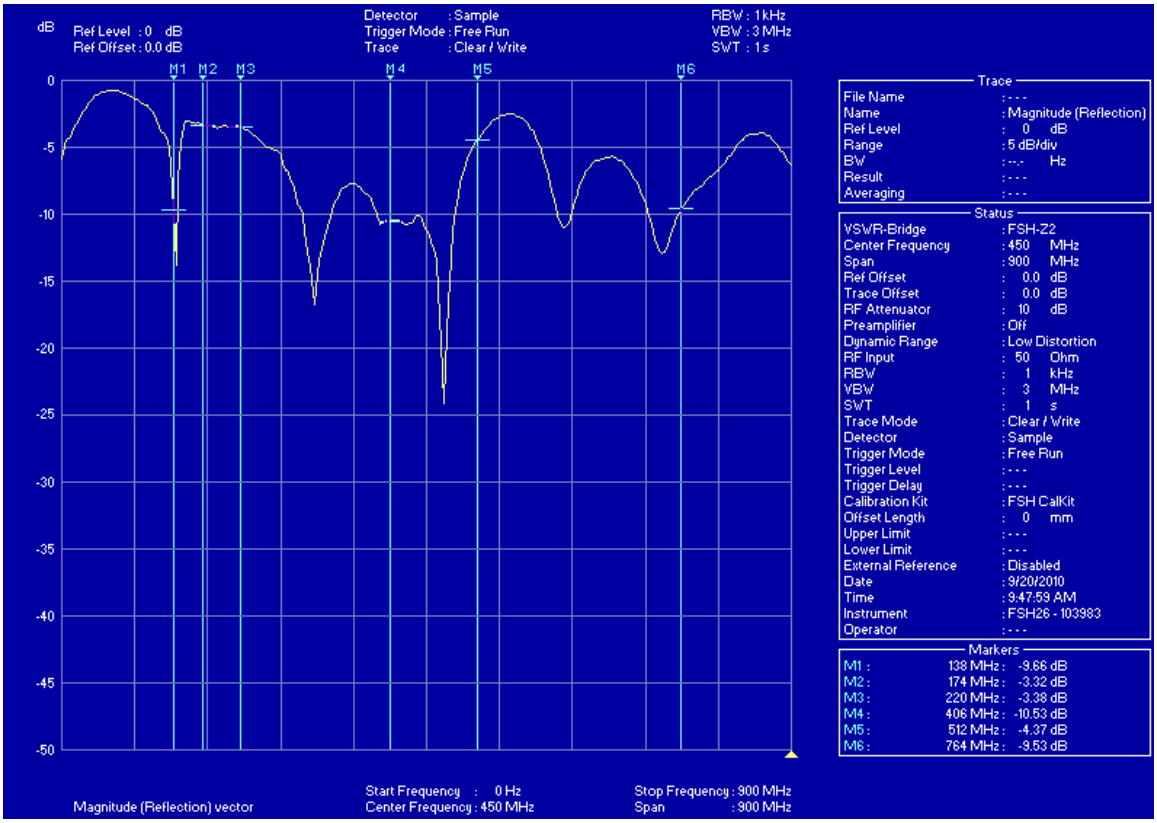

Figure 9: Reflection coefficient looking into antenna tuner radio jack, 24.5 cm open-circuit stub added to relay jack closest to antenna to improve performance at 144 MHz. (Antenna jack terminated into antenna.) Compare to Figure 8.

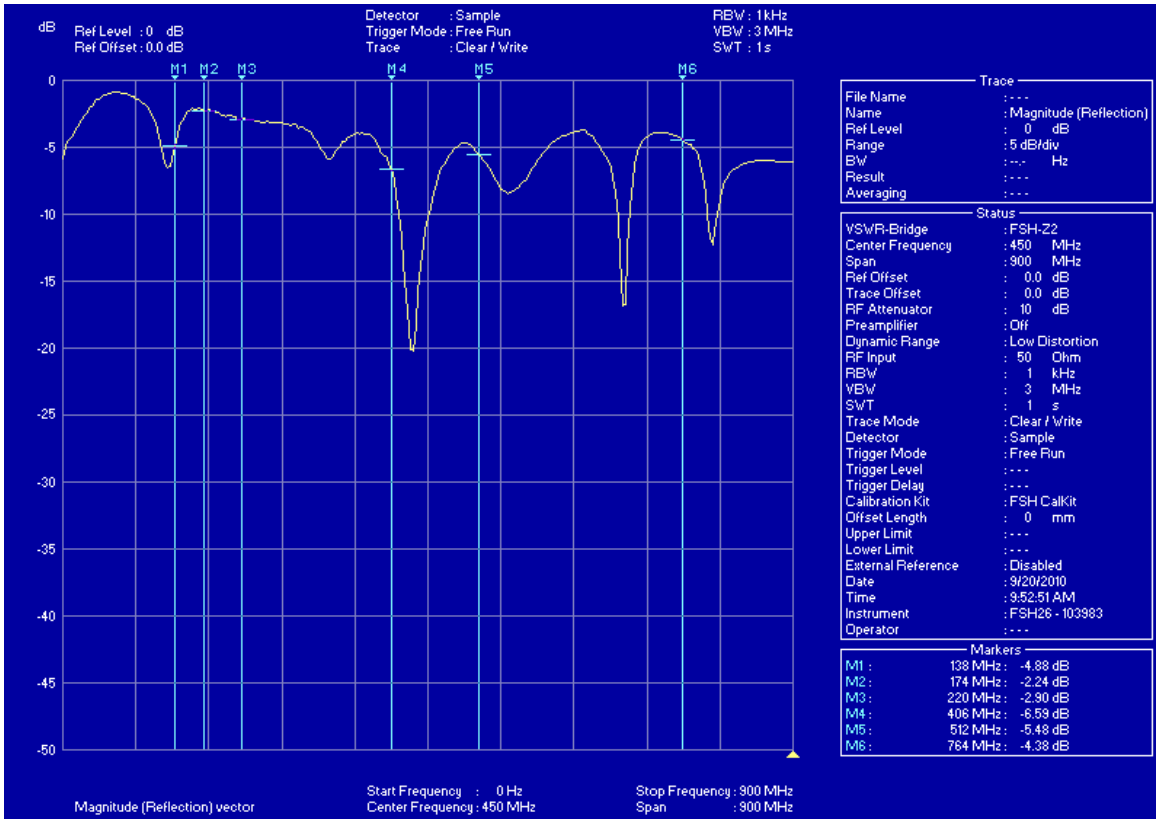

Figure 10: Reflection coefficient looking into antenna tuner antenna jack, 16 cm open-circuit stub added to relay jack furthest from antenna to improve performance at 432 MHz. (Antenna jack terminated into antenna.) Compare to Figure 8.

References

[1] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., http://www.ece.vt.edu/swe/asmr/.

[2] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[3] S. Ellingson, "Measurements of Elements of an LMR Multiband Antenna System Design," Project Report No. 5, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[4] S. Ellingson, "Stubline Tuner," Project Report No. 7, Virginia Polytechnic Inst. & State U., Sep 19, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[5] S. Ellingson, "5-Channel RF Power Detector," Project Report No. 8, Virginia Polytechnic Inst. & State U., Sep 19, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[6] S. Ellingson, "700/800 MHz Bandpass Filter," Project Report No. 9, Virginia Polytechnic Inst. & State U., Sep 19, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[7] S. Ellingson, "Prototype Filter Bank Channel Design," Project Report No. 10, Virginia Polytechnic Inst. & State U., Sep 19, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

Measurements of Elements of an LMR Multiband Antenna System Design

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Contents

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1 Introduction

This report documents some initial measurements of the multiband antenna system design described in our previous project report [1]. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [2]. Section 2 describes the construction of a mock-up of the monopole antenna and associated ground plane, and shows measurements of the antenna self-impedance Z_A. Section 3 uses these measurements to update system performance estimates originally reported in [1]. Section 4 describes a mock-up of the 453 MHz stub tuner described in [1], and measurements of the antenna system when this stub is employed.

2 Antenna Self-Impedance

Figure 1 shows the monopole antenna that was constructed for the measurements. As proposed in [1], it is 23.5 cm in height. The upper 23.1 cm is hollow brass rod 13/32-in. (very nearly 10 mm) in diameter. The lower 0.4 cm is the center conductor of an SMA-type panel connector, which is mounted upside down so that the jack exits underneath the ground plane. This is obviously not the proposed mechanical design, but served to expedite the measurements. The short wooden dowel seen to the left of the monopole is a support used to reduce the chance of damage during the measurements. Subsequent experiments indicate this support does not have a significant effect on the antenna's behavior.

Figure 2 shows the entire structure used in the measurements. The ground plane is 1.79 m $\times$ 1.19 m, constructed from 3 aluminum panels which are bolted together. The ground plane was located approximately 1 m above an asphalt surface. For the purposes of this study, this should be a reasonable surrogate for a vehicular trunk-mounted installation.

All measurements were made using a Rhode & Schwartz FSH6 spectrum analyzer with tracking generator option, fitted with an FSH-Z2 VSWR bridge. The test setup was calibrated the end of coaxial cable with SMA male connector; thus the measurements account for the monopole as well as the ground plane-mounted SMA jack. Smith charts obtained directly from the instrument are included as Appendix A of this report.

Summary results for antenna self-impedance are shown in Figure 3. Shown in the same figure is a result obtained using the simple theoretical model described in [3] and used as a design tool in [1]. Note that the theoretical model does not yield reasonable results in the range 550–750 MHz; this corresponds to the half-wave resonance of the model, over which the impedance is sensitive to the details of the feed region. Also shown is a result obtained using a simple NEC-based method of moments computer simulation, in which the monopole is divided into 13 segments. Both the theoretical and NEC results assume an infinite ground plane. It is interesting to note that the measurements show reasonable agreement with theory for UHF and lower-frequency bands, and also in the 764–862 MHz band. Ironically, the NEC prediction is significantly different from both measurement and theory, even where where measurement and theory are in agreement. We conclude that the theoretical model, despite the infinite ground plane assumption, is reasonable to use in this application; whereas the NEC model needs some work before it can be used.

Figure 4 shows the antenna voltage reflection coefficient (Γ_A in [3]).

3 Revised Performance Estimates Using Measured Z_A Data

The measured Z_A data were used to update the performance estimates for the candidate antenna system design originally presented in [1]. Figure 5 shows the S/N delivered to the receiver with no stubs set. As might be anticipated from the results of the previous section, the measured and theoretical results show good agreement below 300 MHz, and significant discrepancies at higher

Figure 1: Constructed monopole antenna.

Figure 2: Test fixture including antenna and ground plane.

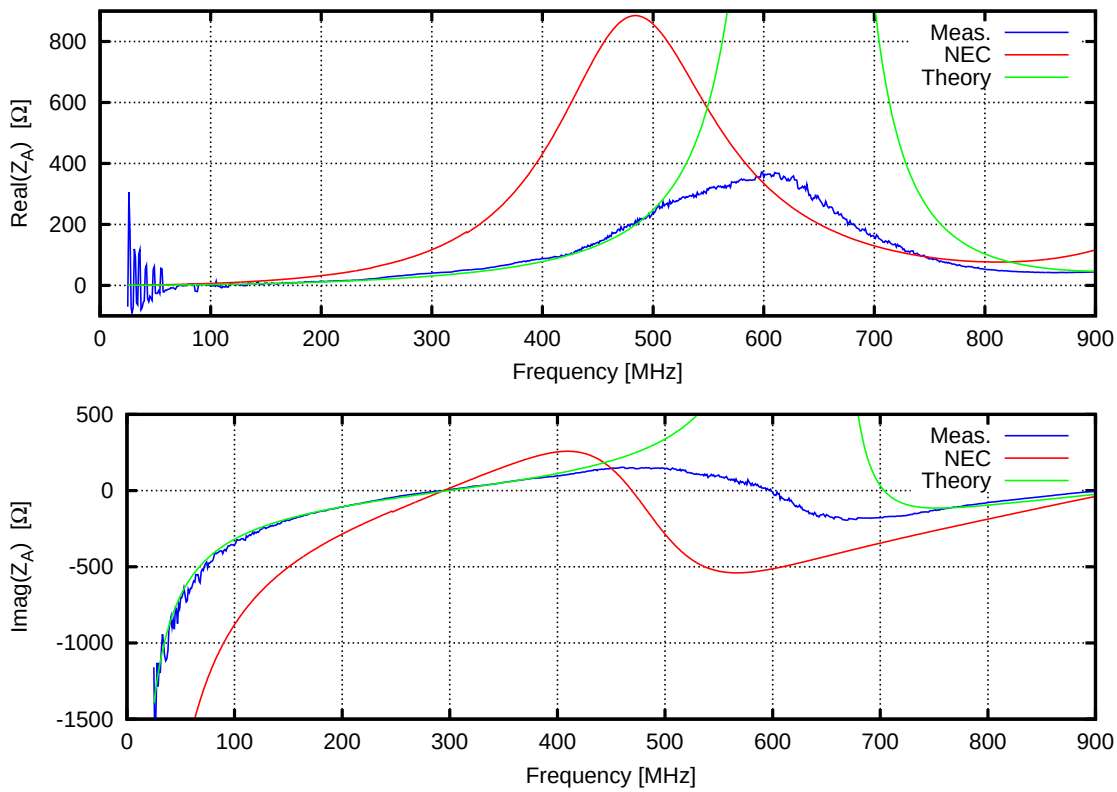

Figure 3: Antenna self-impedance by measurement, NEC, and theory. Note that the "NEC" and "theory" results assume a perfect infinite ground plane.

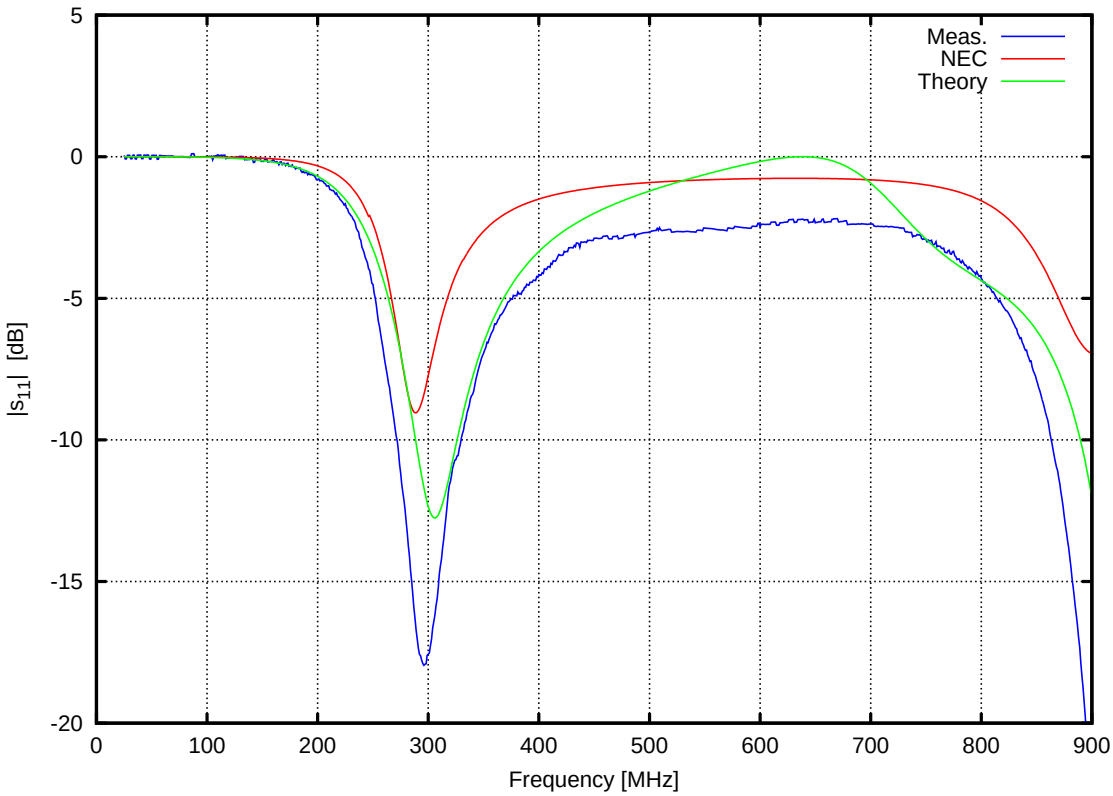

Figure 4: Reflection at the antenna terminals with respect to a $Z_0 = 50\ \Omega$ source. Note that the "NEC" and "theory" results assume a perfect infinite ground plane.

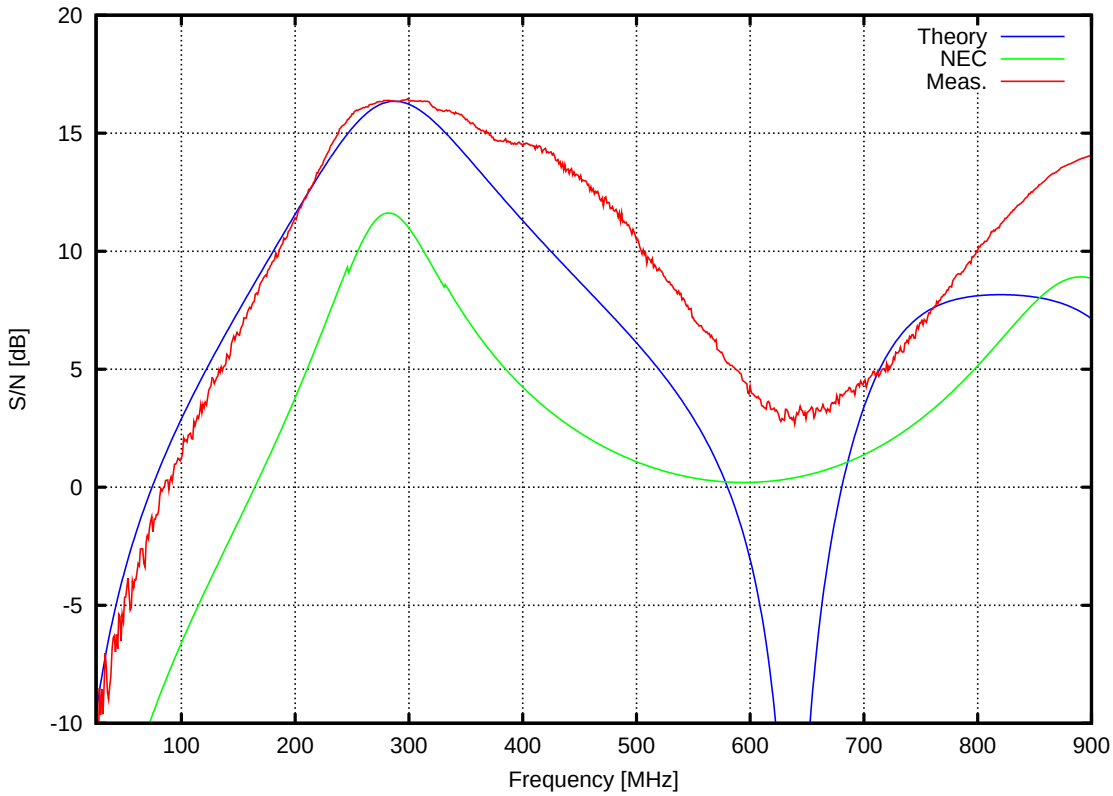

Figure 5: Monopole with no stubs set: Predicted S/N delivered to the transceiver. Note that the "NEC" and "theory" results assume a perfect infinite ground plane.

frequencies. We see no immediate cause for concern in the viability of the candidate design from these results, especially since the measurements suggest receive S/N will be generally higher than predicted.

The updated transmit VSWR prediction was similar updated, and is shown in Figure 8. It is encouraging to see that the agreement between theoretical and measured results is reasonably good over the entire 764–862 MHz band, where the use of stub tuning might be considered optional.

4 453 MHz Stub

The candidate design described in [1] requires switched shunt reactances, with open-circuited stubs as one possible implementation. To test the efficacy of this approach in non-ideal field conditions including uncertainty in the actual value of Z_A, we implemented the 453 MHz stub from [1] using RG-58 coaxial cable. The constructed stub is shown in Figure 7. This is obviously not the proposed mechanical design, but served to expedite the measurements.

A small amount of trimming was required due to construction constraints; however the completed device is estimated to be within a few millimeters of the lengths specified in [1]. The results are shown in terms of VSWR at the output in Figure 8. Note that the agreement with theory is excellent in the region of the nominal frequency (453 MHz), giving confidence that this approach to tuning can be viable in field conditions.

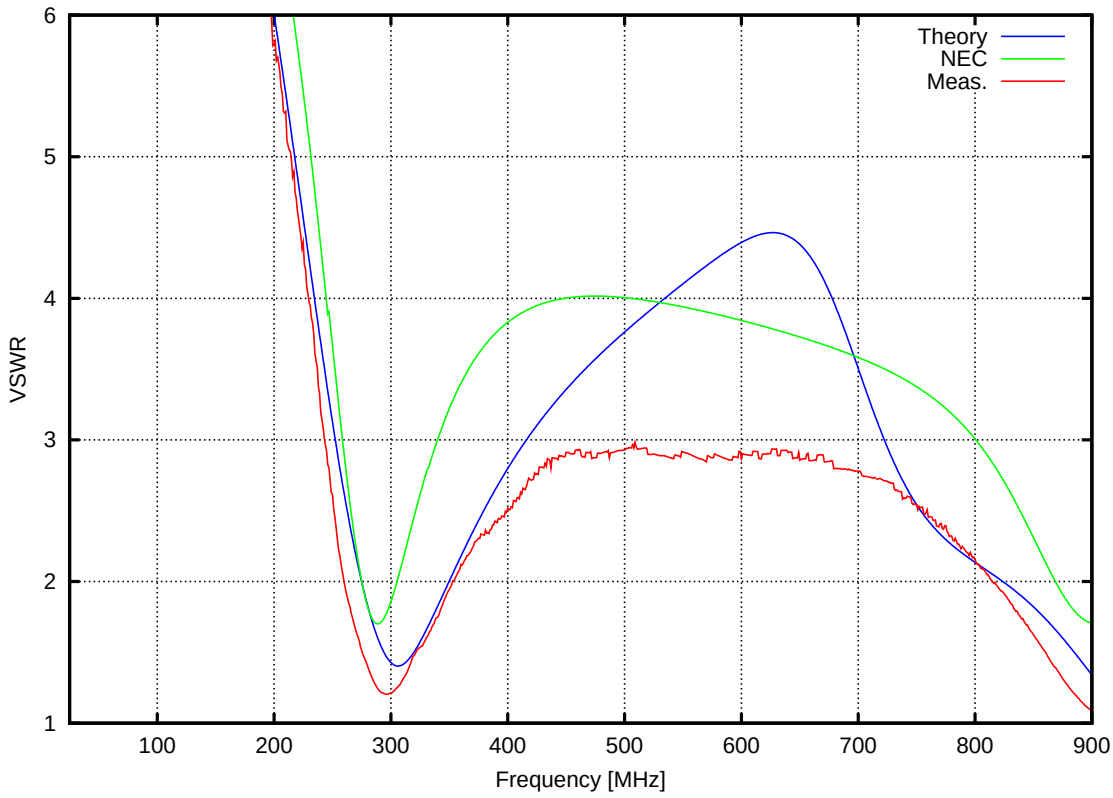

Figure 6: Monopole with no stubs set: Predicted transmit VSWR. Note that the "NEC" and "theory" results assume a perfect infinite ground plane.

Figure 7: 453 MHz tuning stub. The long black cable connects to the antenna, the short black cable is the stub, and measurement is calibrated to the output port of the "tee" connector fabricated from three SMA panel jacks.

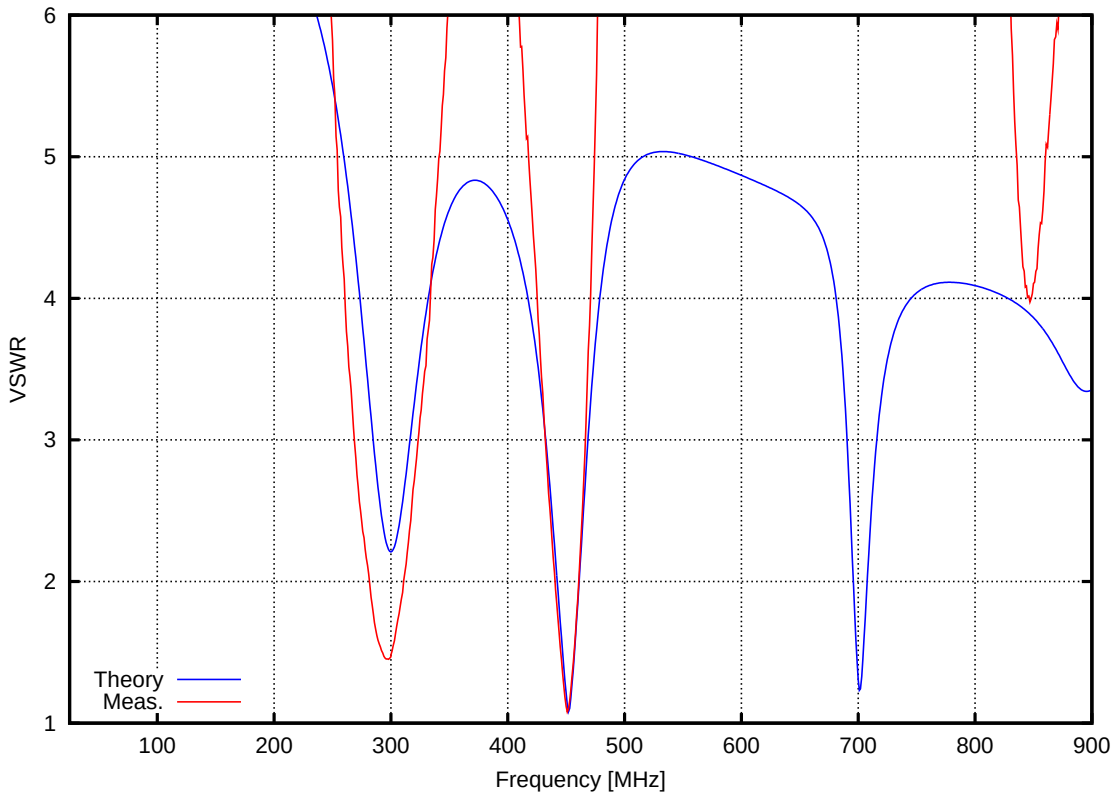

Figure 8: Monopole with 453 MHz stub set: Transmit VSWR. Note that the "theory" result assumes a perfect infinite ground plane.

A Smith Charts

This appendix contains the Smith charts acquired in the process of making the measurements described in this report. Figures 9–11 pertain to the antenna self-impedance measurements. Figures 12–14 pertain to the 453 MHz stub system measurements.

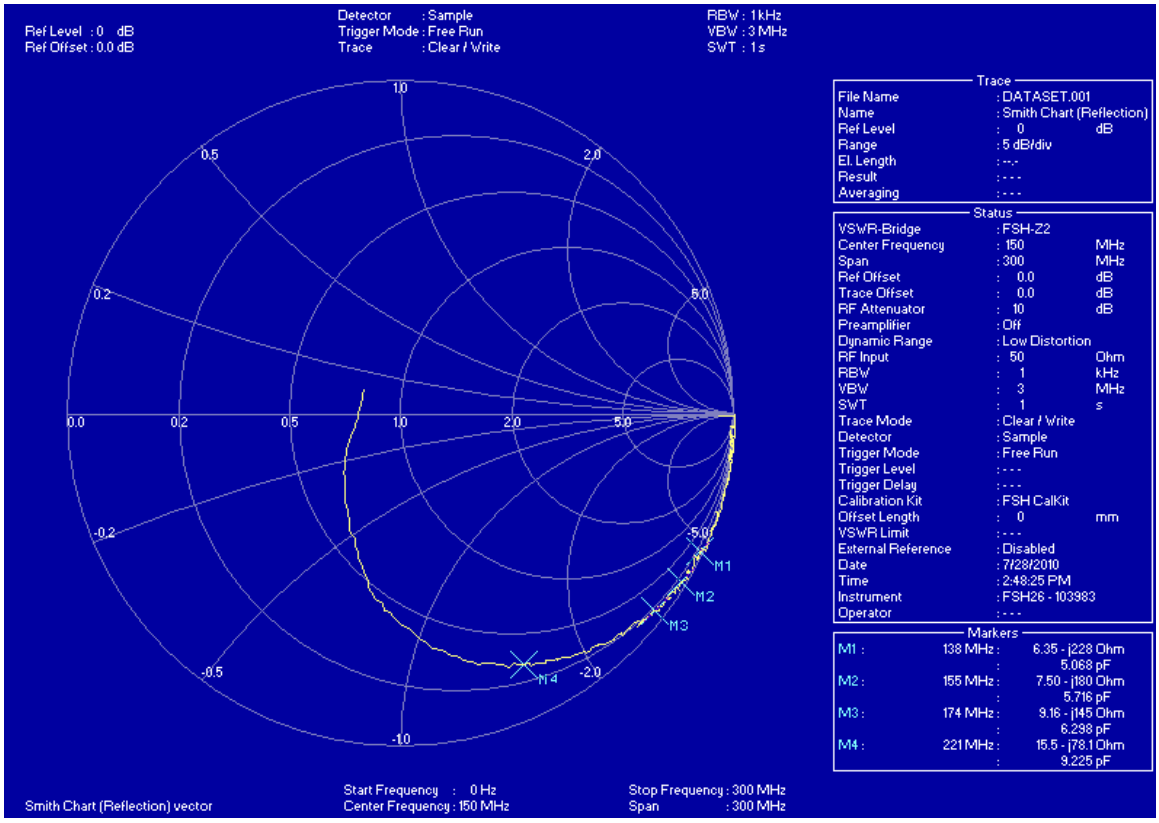

Figure 9: Z_A, 0–300 MHz.

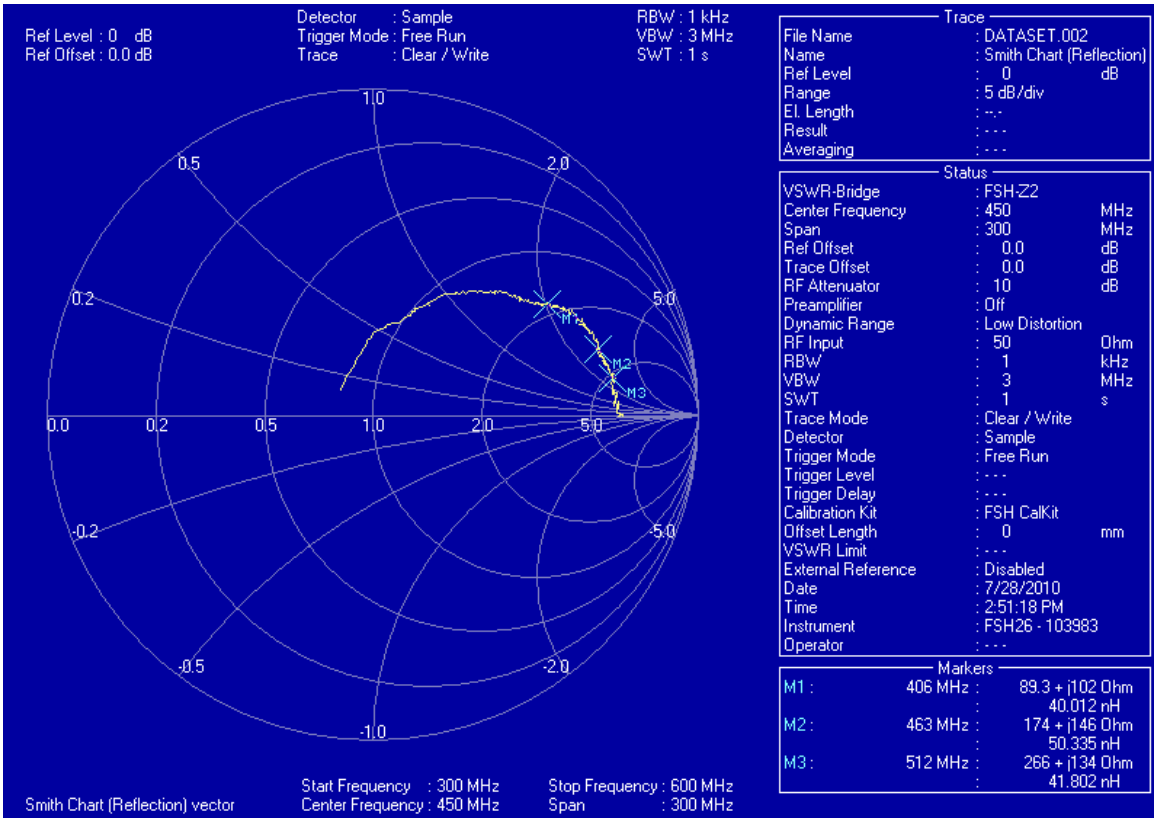

Figure 10: Z_A, 300–600 MHz.

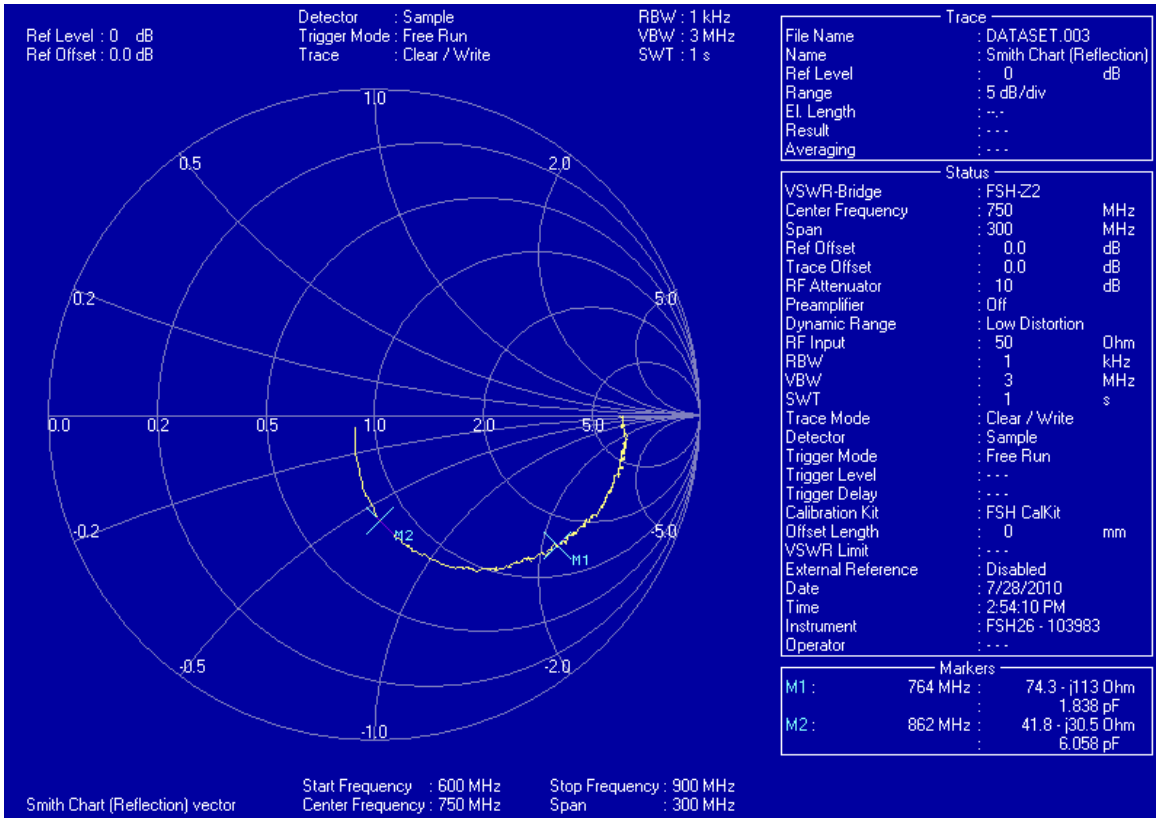

Figure 11: Z_A, 600–900 MHz.

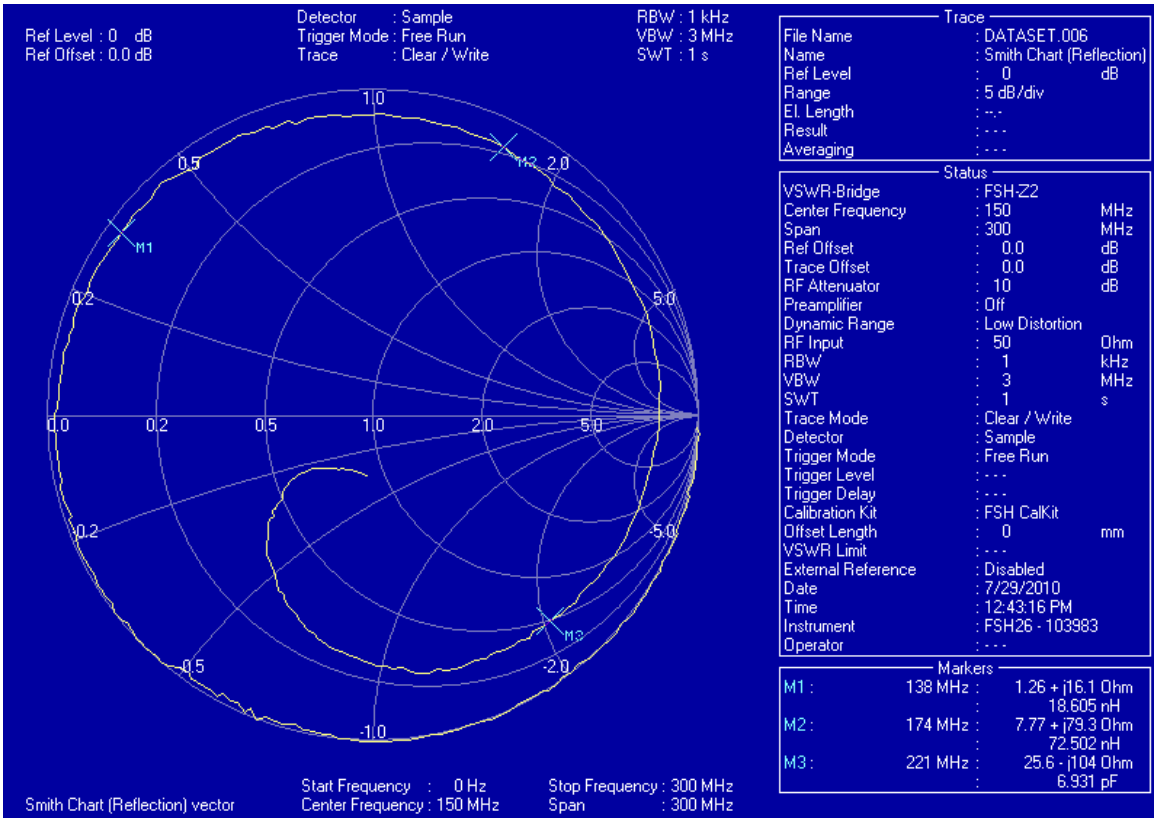

Figure 12: System with 453 MHz stub, 0–300 MHz.

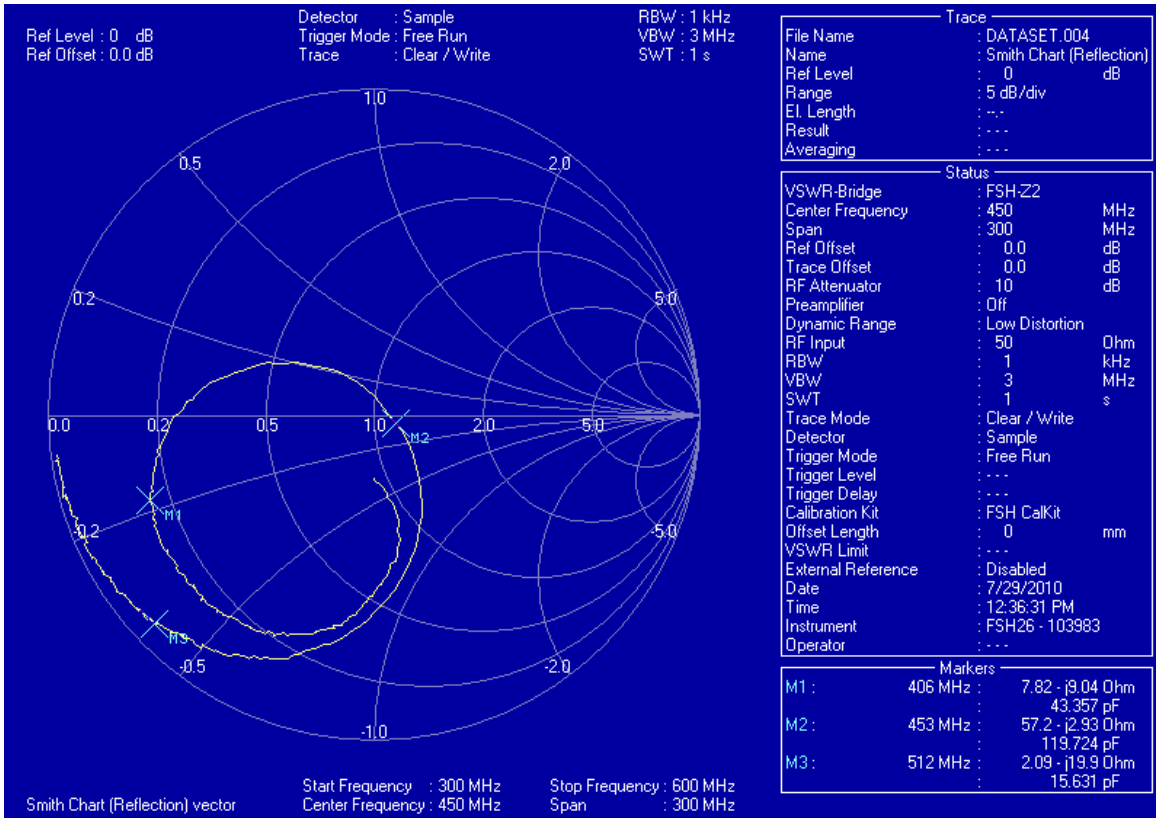

Figure 13: System with 453 MHz stub, 300–600 MHz.

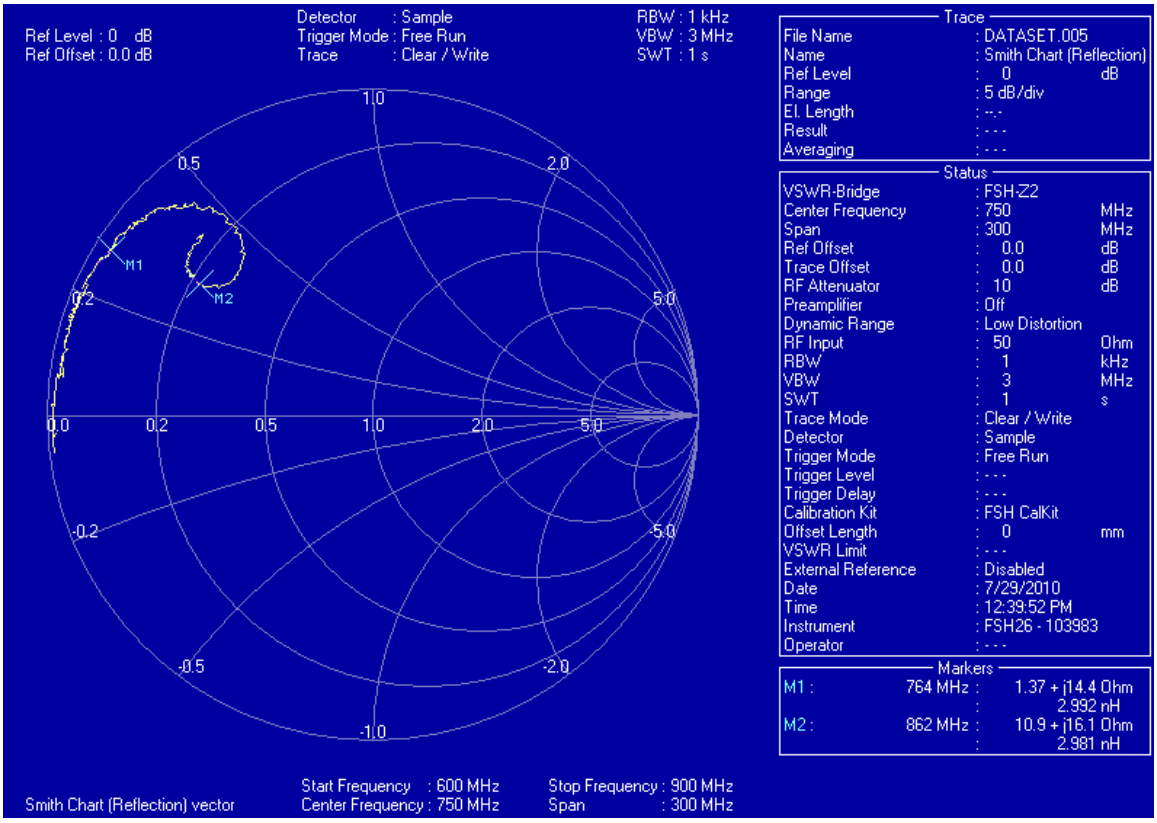

Figure 14: System with 453 MHz stub, 600–900 MHz.

References

[1] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

[2] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., http://www.ece.vt.edu/swe/asmr/.

[3] S. Ellingson, "Methodology for Analysis of LMR Antenna Systems," Project Report No. 3, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] http://www.ece.vt.edu/swe/asmr/.

Stubline Tuner

Steve Ellingson*

September 19, 2010

Contents

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1 Introduction

This report documents the design of a stubline tuner. The tuner is part of an antenna system, currently in development, described (in concept) in [1]. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [2].

2 Design

The constructed stubline is shown in Figure 1. The stubline consists of a 50Ω microstrip line with 10 switchable stubs, spaced 1.0 cm apart. The total length of the stubline (between the footprint centers of the SMA input and output jacks) is 11.4 cm. The distance from the left connector (J1) to the first stub junction is 0.9 cm. The length of the stub (measured from junction point on the primary transmission line to the footprint center of the stub's SMA connector) is 1.3 cm, and can be extended by attaching SMA connectorized coaxial cable.

The printed circuit board is 2-layer FR4 (relative permittivity ≈ 4.5) 0.062 in (1.575 mm) thick. The primary transmission line is 0.11 in (2.8 mm) wide. The velocity factor prior to installation of the relays is estimated to be 60%.

The schematic and board layout are shown in Figures 2 and 3, respectively. Switching is done using NAiS Model AGN2104H single-coil latching relays. Since the relays are of the latching variety, no power is required except to change state. A voltage of about 2.5 V across the coil is sufficient to activate the latch; applying a signal of the opposite polarity changes the state.

3 Performance

Figure 4 shows s_{21} through the stubline with all relays open (i.e., no stubs connected). The worst case insertion loss is about 0.9 dB. To isolate the effect of the (open) relays from the primary transmission line, the latter was also measured *prior* to installing the relays; the result is shown in Figure 5. In this case the worst case insertion loss is about 0.4 dB.

Figure 6 shows s_{11} measured at the left (J1) jack, again with all relays open. The worst case return loss is about 8 dB, corresponding to a VSWR of 2.3. s_{22} is essentially the same.

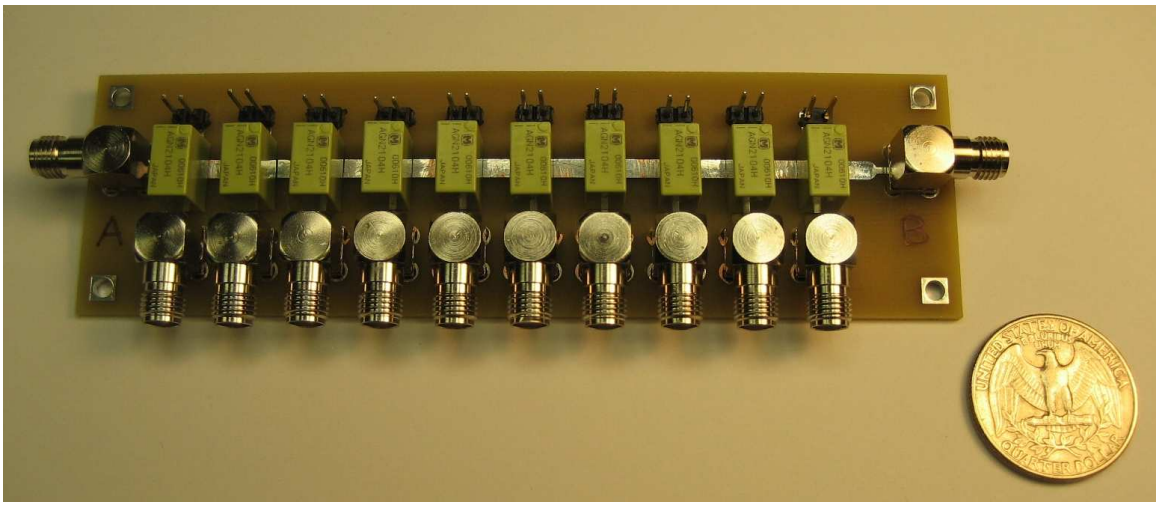

Figure 1: Stubline.

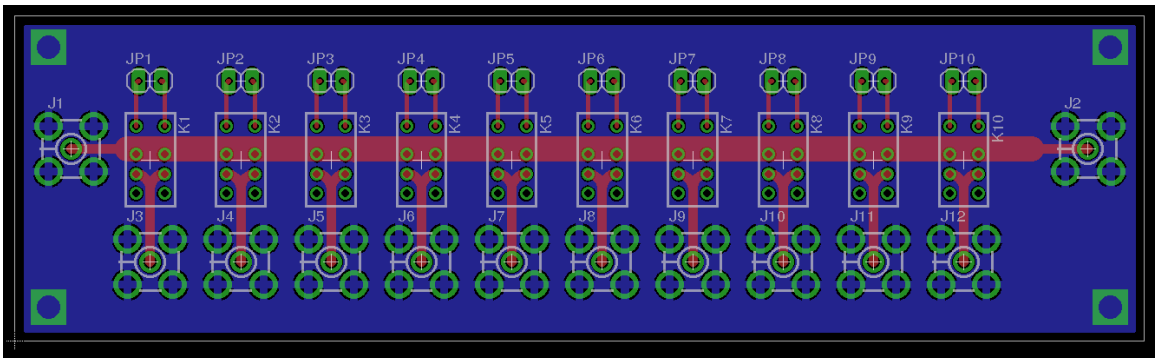

Figure 2: Stubline PCB layout.

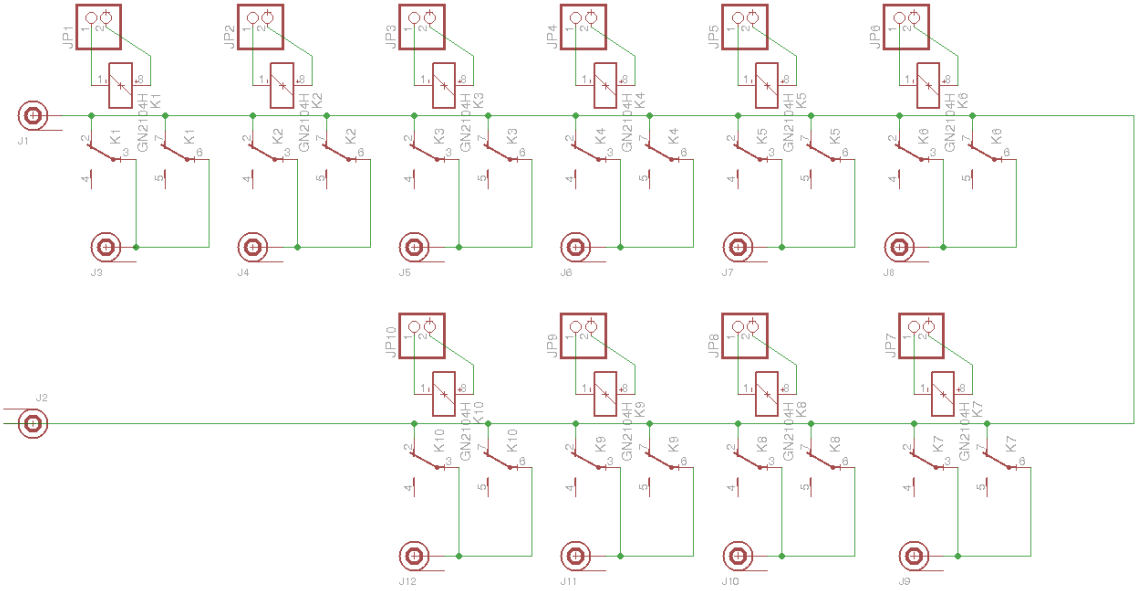

Figure 3: Stubline schematic.

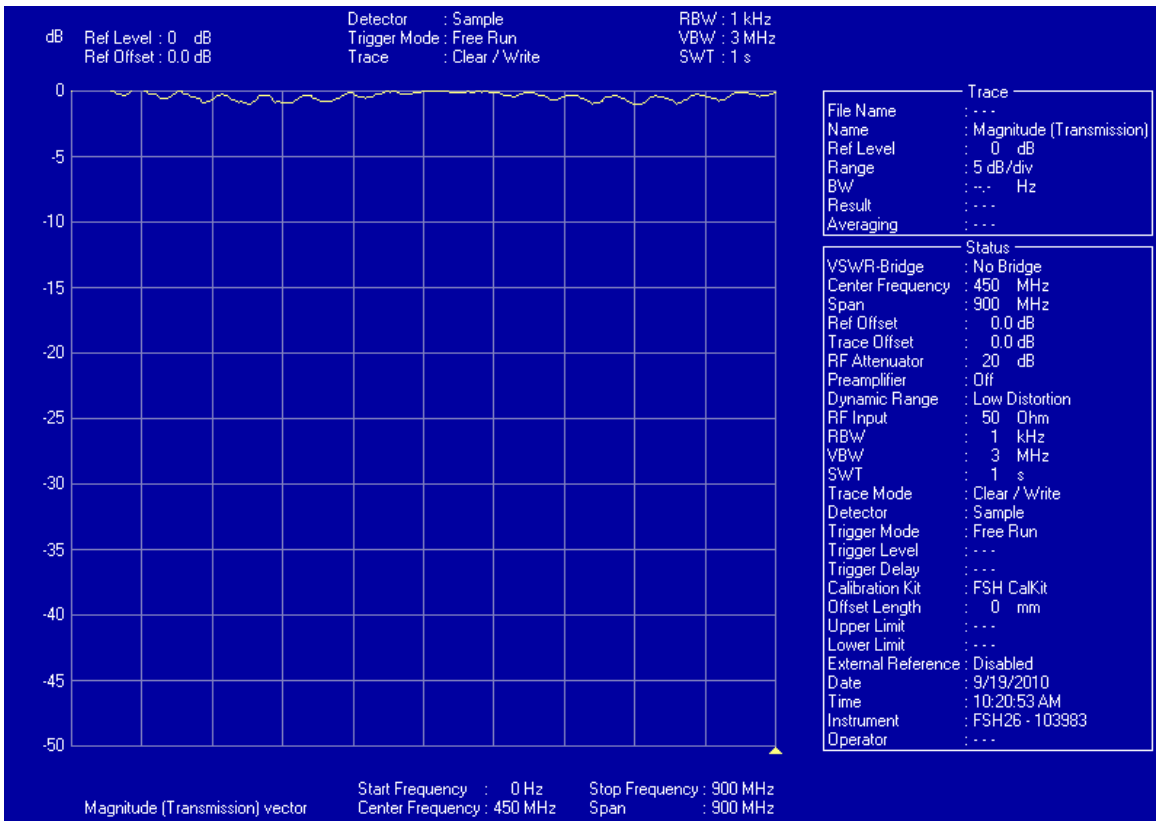

Figure 4: Stubline s_{21}, all relays open.

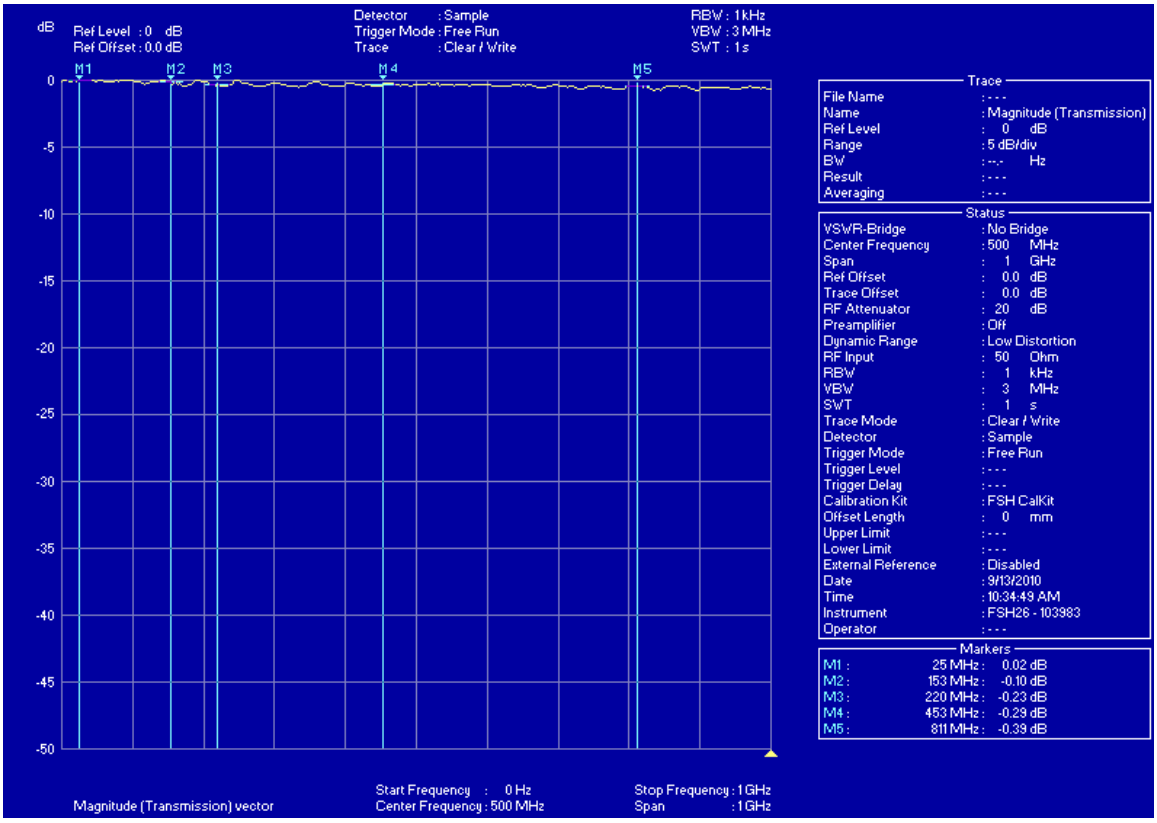

Figure 5: Stubline s_{21}, prior to installation of relays.

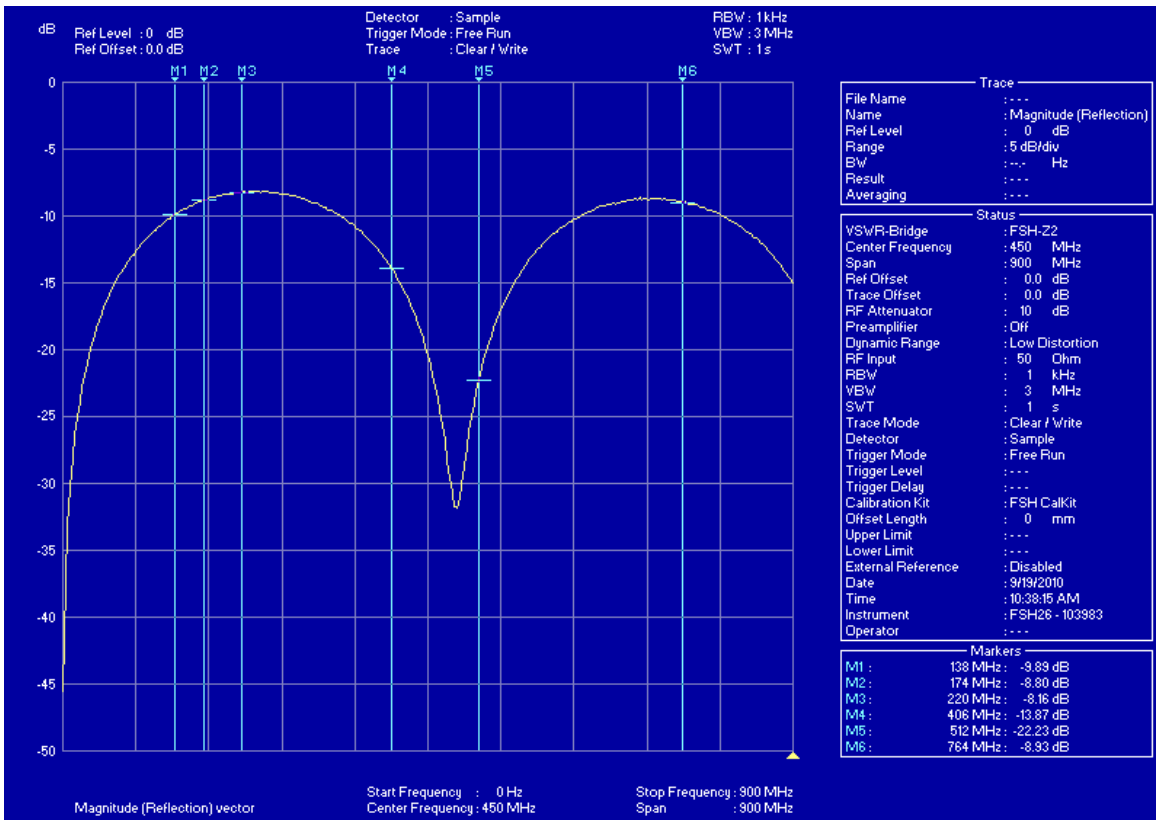

Figure 6: Stubline s_{11}, all relays open.

References

[1] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] `http://www.ece.vt.edu/swe/asmr/`.

[2] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., `http://www.ece.vt.edu/swe/asmr/`.

5-Channel RF Power Detector

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Contents

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1 Introduction

This report documents the design of a 5-channel RF power detector. The detector is part of an antenna system, currently in development, described (in concept) in [1]. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [2].

2 Design

The constructed 5-channel detector is shown in Figure 1. Each detector employs a 1N5711 Schottky diode (Digikey PN 1N5711W-FDICT-ND) to convert the applied RF signal into a DC voltage representing the input signal power. Each detector uses a different value shunt capacitor, in order to accommodate a wide range of input frequencies.

The schematic and board layout are shown in Figures 2 and 3, respectively. The printed circuit board is 2-layer FR4 0.062 in (1.575 mm) thick. The capacitors are ceramic NPO type, 0805 package, from an AVX designer's kit (Digikey PN 478-5617-ND). The resistors are 0.125-W 0.1% thin film type, 0805 package, from an SEI designer's kit (Digikey PN RNCS0805BTEKITKIT-ND). MMCX connectors are used for the input terminals.

3 Performance

Table 1 shows the response of each detector channel to RF signals at a variety of frequencies and input powers. Note that the performance is not particularly sensitive to the value of the capacitance.

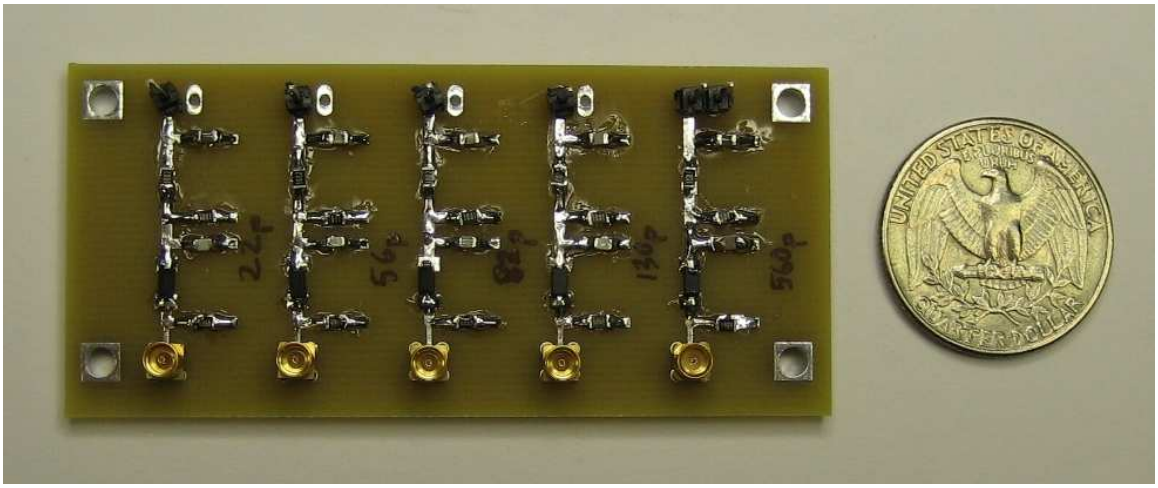

Figure 1: 5-channel RF power detector.

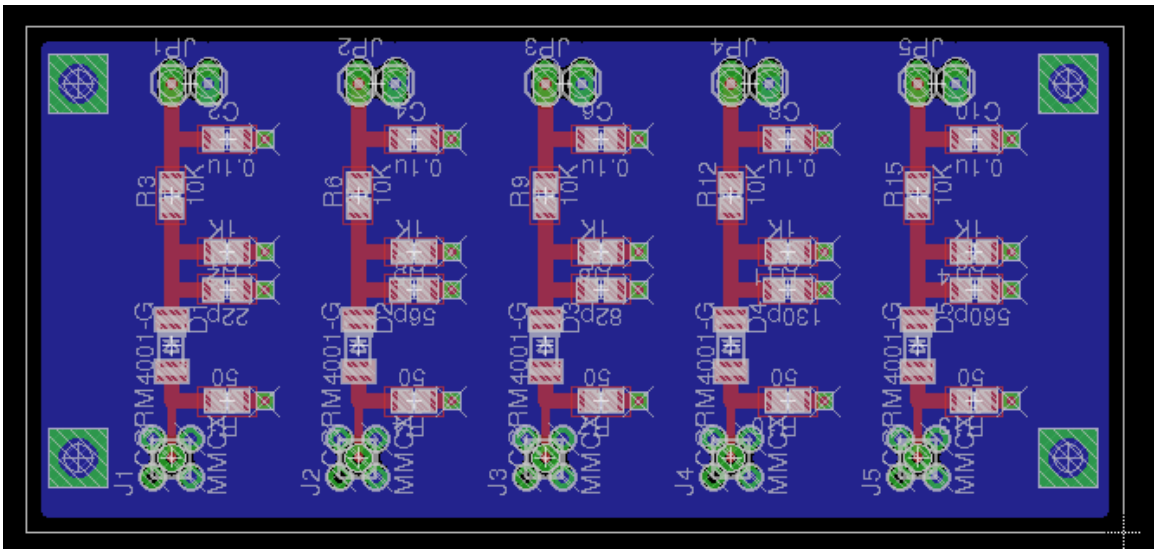

Figure 2: Detector PCB layout.

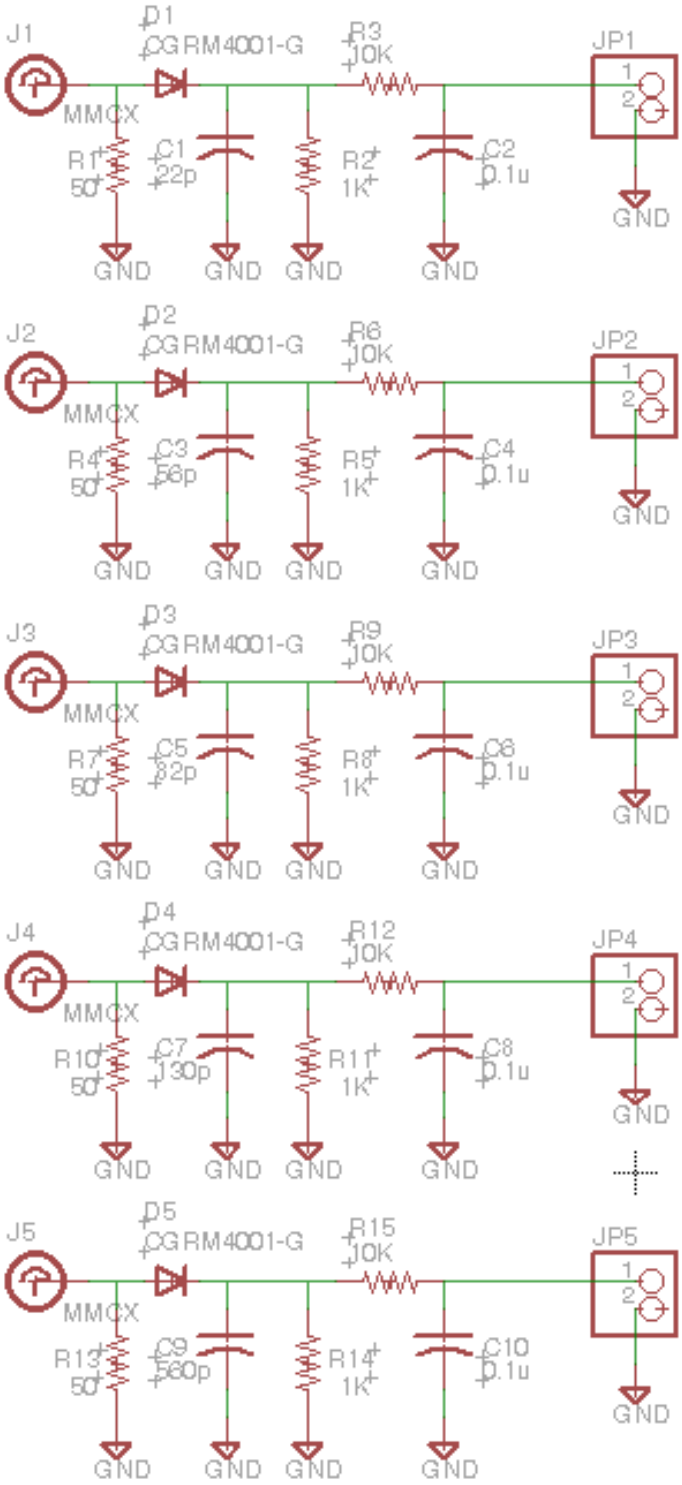

Figure 3: Detector schematic.

Cap	Frequency	RF Level	Output Voltage
560 pF	25 MHz	0 dBm	0.01 V
560 pF	25 MHz	5 dBm	0.13 V
560 pF	25 MHz	10 dBm	0.37 V
560 pF	25 MHz	15 dBm	0.76 V
560 pF	25 MHz	20 dBm	1.48 V
560 pF	50 MHz	20 dBm	1.43 V
560 pF	143 MHz	20 dBm	1.43 V
560 pF	220 MHz	20 dBm	1.40 V
560 pF	453 MHz	20 dBm	1.46 V
560 pF	811 MHz	20 dBm	1.36 V
130 pF	153 MHz	10 dBm	0.38 V
82 pF	220 MHz	10 dBm	0.38 V
56 pF	453 MHz	10 dBm	0.39 V
22 pF	811 MHz	10 dBm	0.40 V

Table 1: Measured detector response. "Cap" refers to the value of the shunt capacitor following the diode.

References

[1] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] `http://www.ece.vt.edu/swe/asmr/`.

[2] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., `http://www.ece.vt.edu/swe/asmr/`.

700/800 MHz Bandpass Filter

Steve Ellingson*

September 19, 2010

Contents

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1 Introduction

This report documents the design of a 700/800 MHz bandpass filter. The filter is part of an antenna system, currently in development, described (in concept) in [1]. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [2].

2 Design

The constructed filter is shown in Figure 1. The printed circuit board is 2-layer FR4 (relative permittivity ≈ 4.5) 0.062 in (1.575 mm) thick. The transmission lines are 0.11 in (2.8 mm) wide, and the velocity factor is estimated to be 60%. The filter employs a single open-circuited stub which is $\lambda/4$ at 450 MHz in order to create a null, followed by 3 short-circuited stubs which are $\lambda/4$ at 1.1 GHz to level the gain over the desired passband. The lines between stubs are each $\lambda/4$ at 1.1 GHz. No particular effort was made to optimize the performance or dimensions of this filter. MMCX connectors are used at input and output.

3 Performance

Figure 2 shows s_{21} through the filter. The worst case in-band insertion loss is about 0.5 dB. The peak insertion loss below 500 MHz is about 13 dB, at about 250 MHz.

Figure 1: 700/800 MHz BPF.

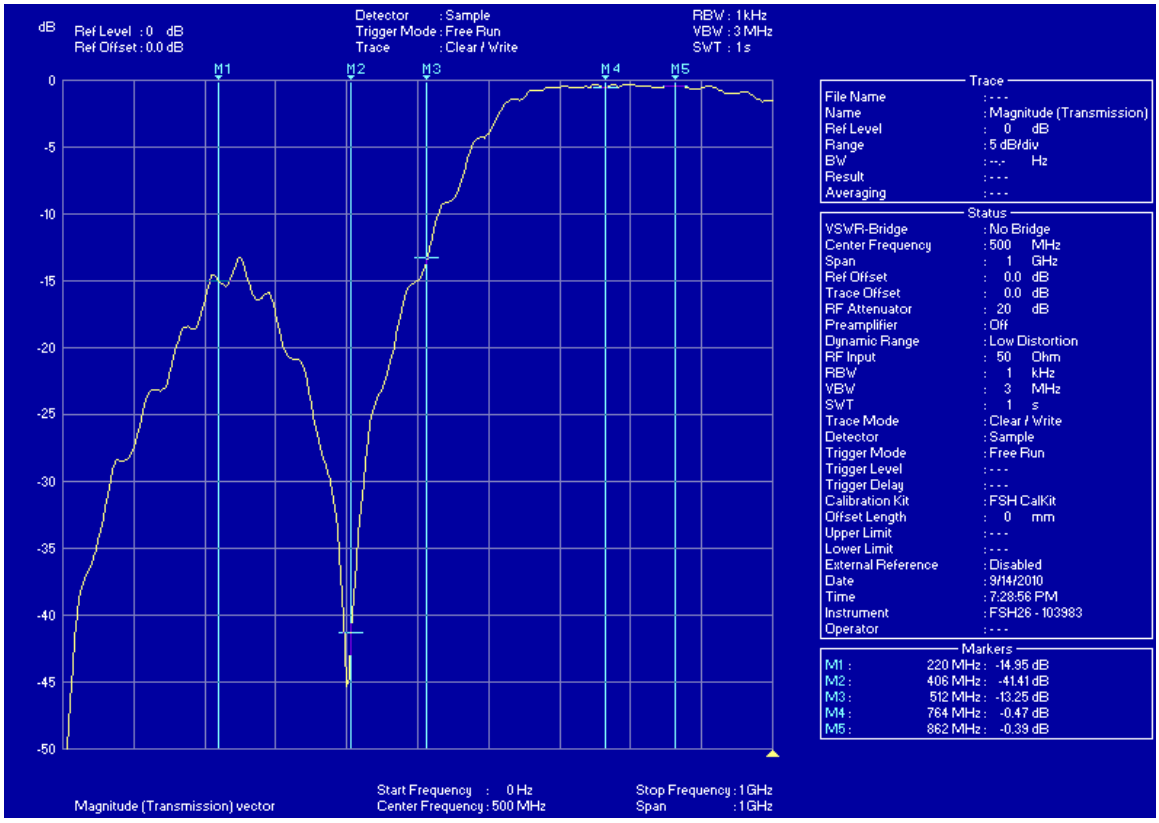
dB
Ref Level : 0 dB
Ref Offset : 0.0 dB
Detector : Sample
Trigger Mode : Free Run
Trace : Clear / Write
RBW : 1kHz
VBW : 3 MHz
SWT : 1 s
M1
M2
M3
M4
M5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Magnitude (Transmission) vector
Start Frequency : 0 Hz
Center Frequency : 500 MHz
Stop Frequency : 1 GHz
Span : 1 GHz
Trace
File Name : - - -
Name : Magnitude (Transmission)
Ref Level : 0 dB
Range : 5 dB/div
BW : --.- Hz
Result : - - -
Averaging : - - -
Status
VSWR-Bridge : No Bridge
Center Frequency : 500 MHz
Span : 1 GHz
Ref Offset : 0.0 dB
Trace Offset : 0.0 dB
RF Attenuator : 20 dB
Preamplifier : Off
Dynamic Range : Low Distortion
RF Input : 50 Ohm
RBW : 1 kHz
VBW : 3 MHz
SWT : 1 s
Trace Mode : Clear / Write
Detector : Sample
Trigger Mode : Free Run
Trigger Level : - - -
Trigger Delay : - - -
Calibration Kit : FSH CalKit
Offset Length : 0 mm
Upper Limit : - - -
Lower Limit : - - -
External Reference : Disabled
Date : 9/14/2010
Time : 7:28:56 PM
Instrument : FSH26 - 103983
Operator : - - -
Markers
M1 : 220 MHz : -14.95 dB
M2 : 406 MHz : -41.41 dB
M3 : 512 MHz : -13.25 dB
M4 : 764 MHz : -0.47 dB
M5 : 862 MHz : -0.39 dB

Figure 2: s_{21}.

References

[1] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] `http://www.ece.vt.edu/swe/asmr/`.

[2] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., `http://www.ece.vt.edu/swe/asmr/`.

Prototype Filter Bank Channel Design

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September 19, 2010

Contents

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1 Introduction

This report documents the design and evaluation of prototype bandpass filter channels for a filter bank. The filter bank is being developed as part of an antenna system project described (in concept) in [1]. This antenna system is being developed as part of our project "Antenna Systems for Multiband Mobile & Portable Radio" [2].

The filter bank is intended to separate a single RF input into separate channels corresponding to the VHF Low (VHF-L; 25–50 MHz), VHF High (VHF-H, 138–174 MHz), 220–222 MHz, UHF (406–512 MHz), and 700/800 MHz bands. The 700/800 MHz bandpass filter was designed separately and is documented in a previous technical report [3]. This report documents the remaining 4 channels. It is found by measurements of the prototype channel filters that the initial design is tuned slightly low in frequency, and will require revision before use as a multiplexer. The design will probably work as the filter bank used in the transmit band detection circuit, but should be revised in that application as well.

2 Design

The constructed filter bank is shown in Figure 1. Figures 2 and 3 show the circuit board and schematic, respectively. The printed circuit board is 2-layer FR4 0.062 in (1.575 mm) thick. MMCX connectors are used at input and all outputs. The capacitors are ceramic NPO type, 0805 package, from an AVX designer's kit (Digikey PN 478-5617-ND). The inductors are EPCOS "SIMID" series 0805 package devices from a designer's kit (Digikey PN 495-1685-ND). The resistors are 0.125-W 0.1% thin film type, 0805 package, from an SEI designer's kit (Digikey PN RNCS0805BTEKITKIT-ND). The printed circuit board includes a solder bridge junction adjacent to the common jack, which allows each channel to be checked separately or in various combinations. A fifth channel jack is included to allow connection of a 700/800 MHz channel.

3 Performance

Figures 4–7 show s_{21} through each of the four filters on the board. Note that the bandpasses appear to be 10%–30% low in frequency relative to the desired bandpass response. Also, the insertion loss of the 220 MHz is unacceptable.

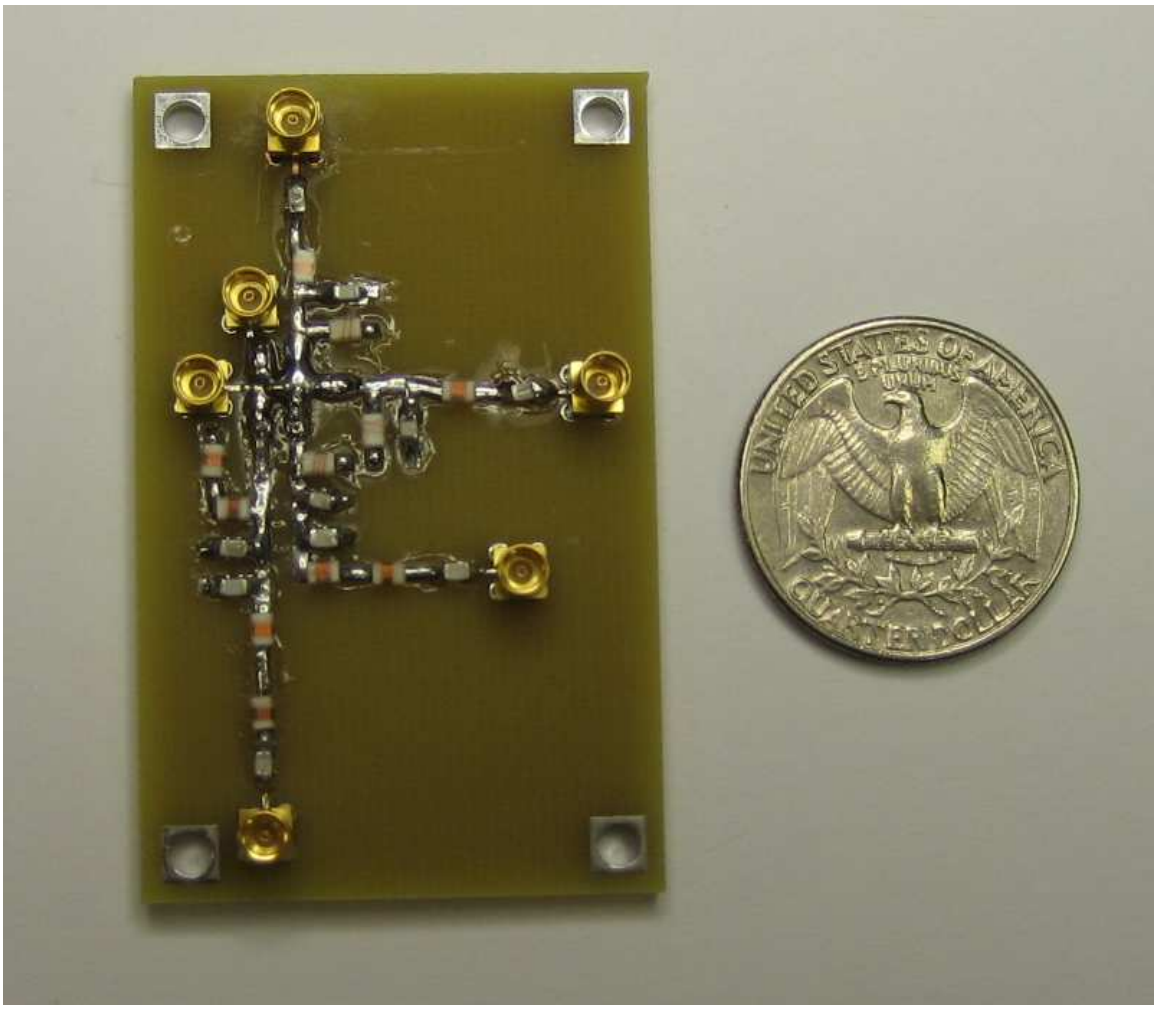

Figure 1: Filter bank.

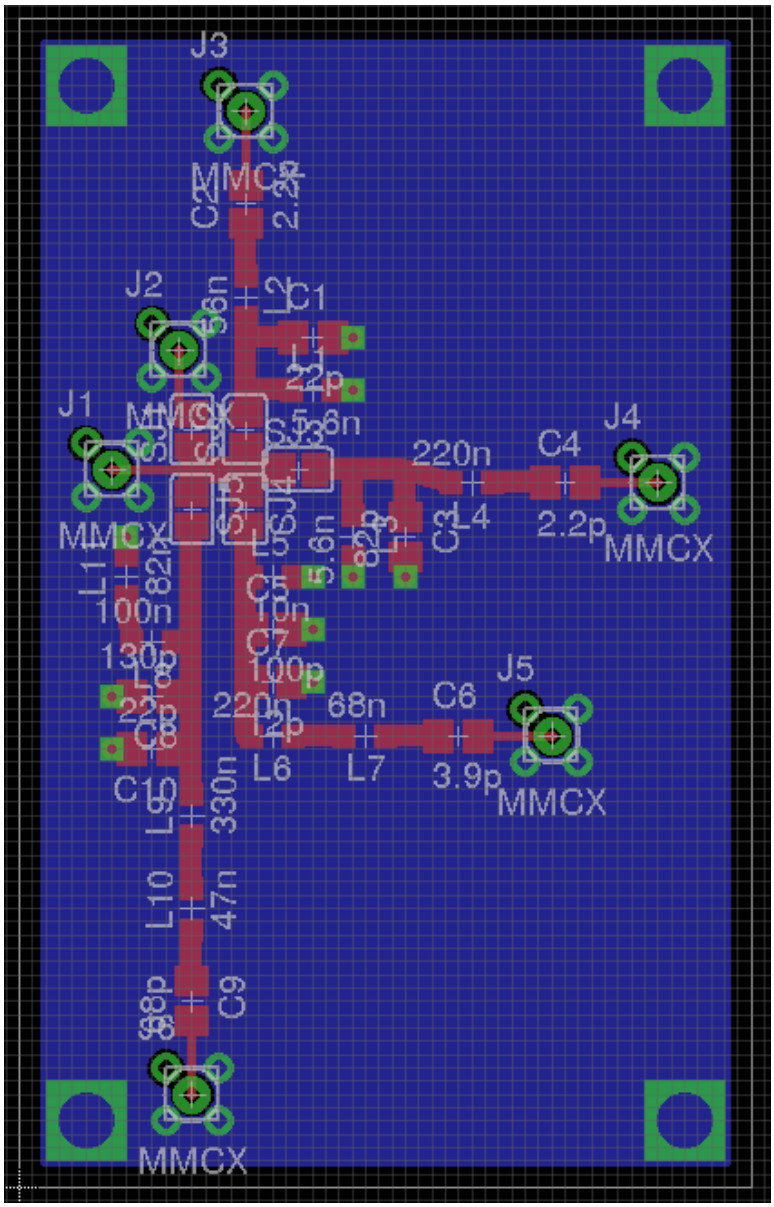

Figure 2: Filter bank board.

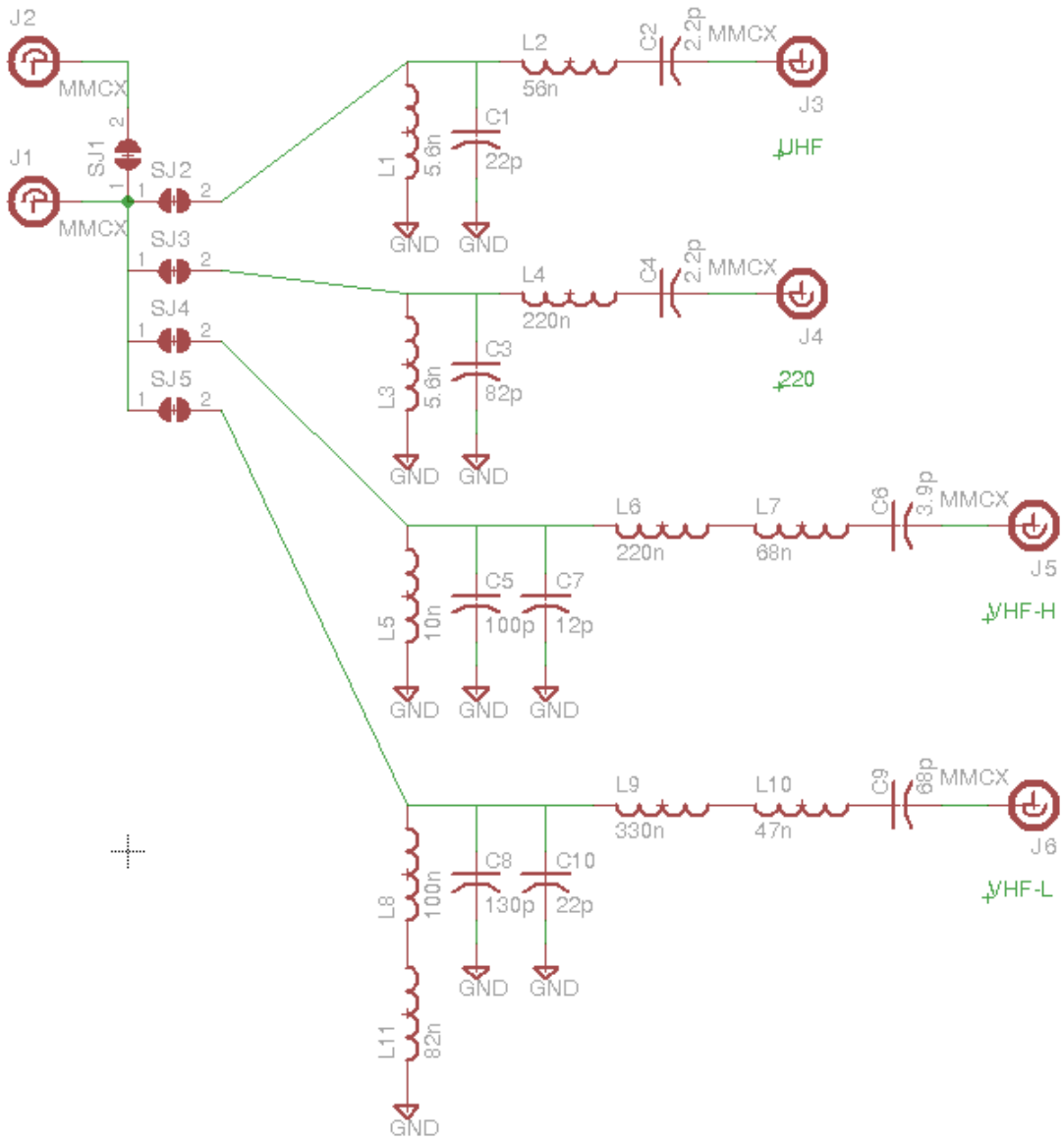

Figure 3: Filter bank schematic.

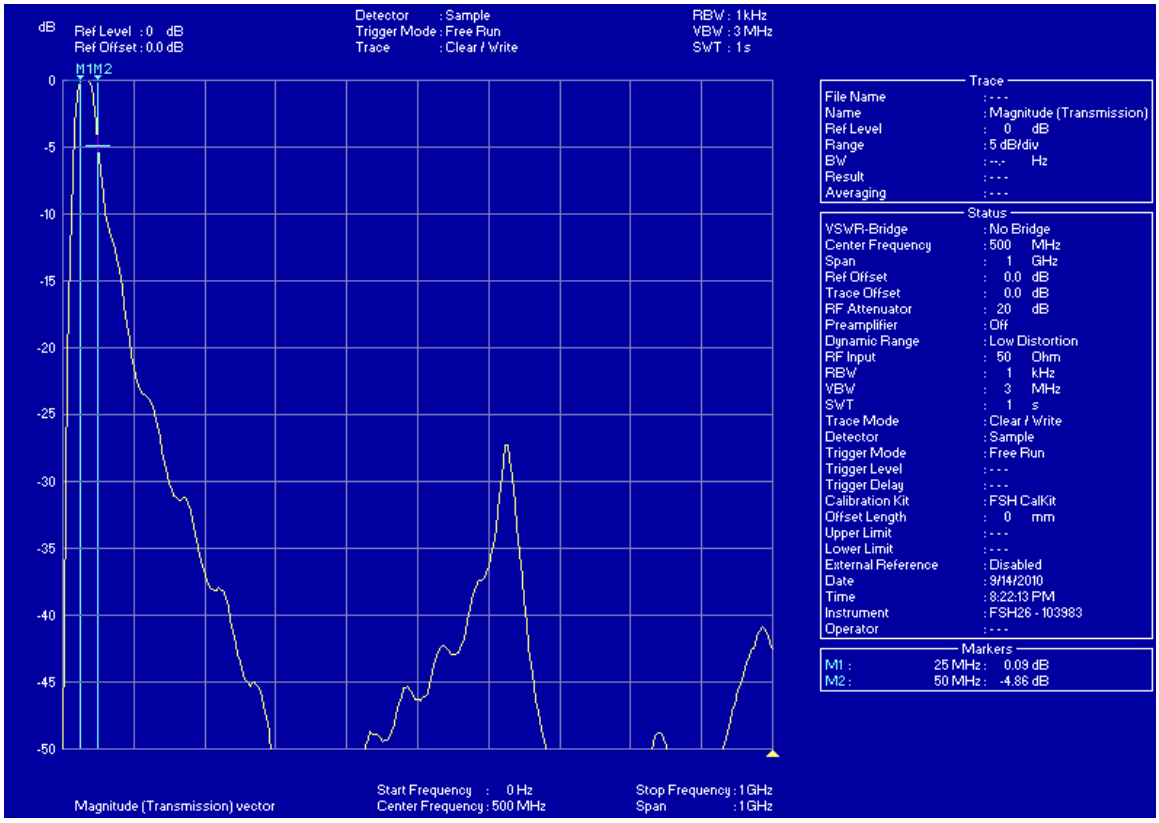

Figure 4: s_{21}, VHF-L Channel.

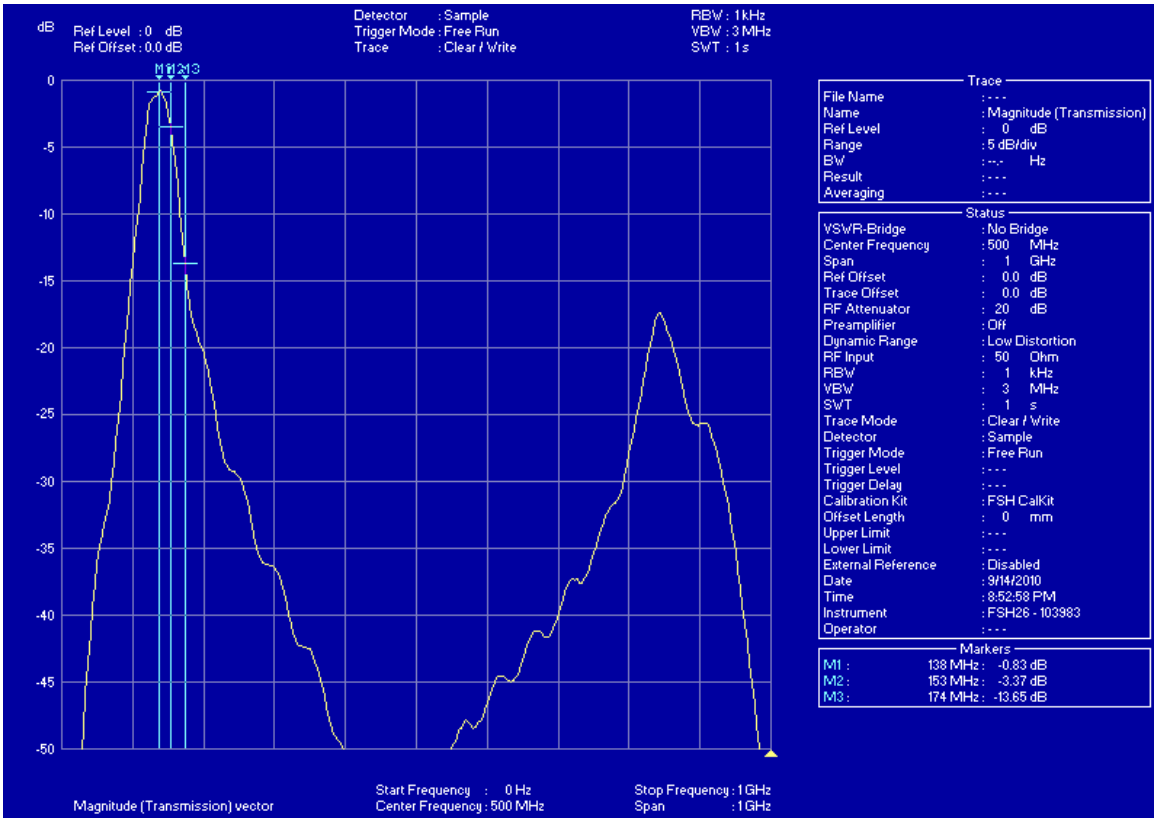

Figure 5: s_{21}, VHF-H Channel.

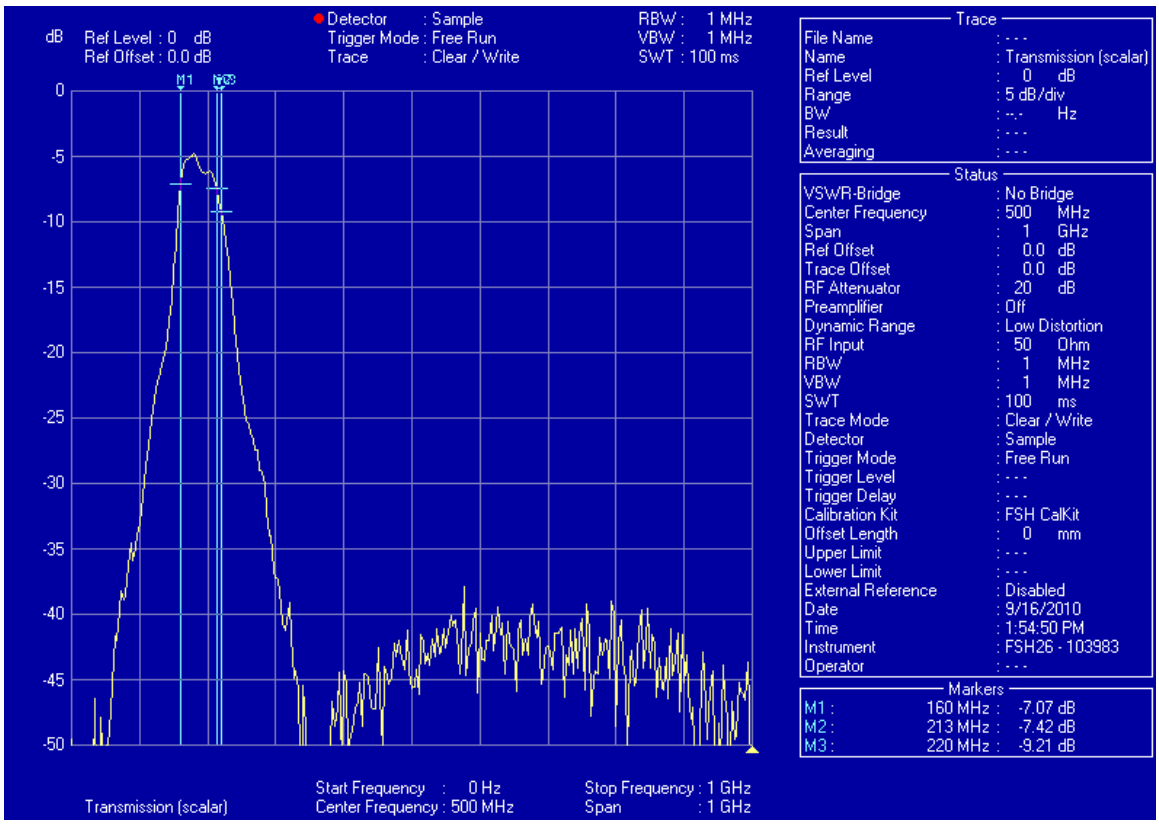

Figure 6: s_{21}, 220 MHz Channel.

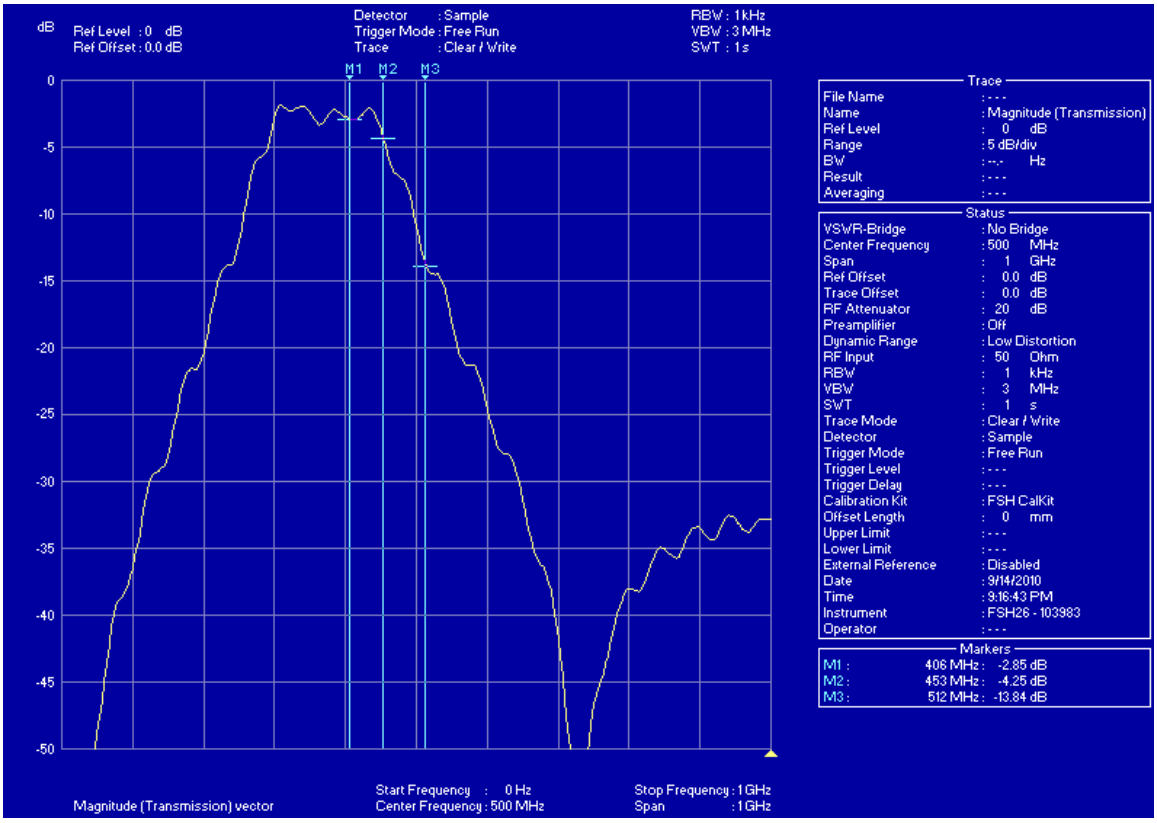

Figure 7: s_{21}, UHF Channel.

References

[1] S. Ellingson, "Candidate Design for a Multiband LMR Antenna System Using a Rudimentary Antenna Tuner," Project Report No. 4, Virginia Polytechnic Inst. & State U., Jun 30, 2010. [online] `http://www.ece.vt.edu/swe/asmr/`.

[2] Project web site, "Antenna Systems for Multiband Mobile & Portable Radio," Virginia Polytechnic Inst. & State U., `http://www.ece.vt.edu/swe/asmr/`.

[3] S. Ellingson, "700/800 MHz Bandpass Filter," Project Report No. 9, Virginia Polytechnic Inst. & State U., Sep 19, 2010. [online] `http://www.ece.vt.edu/swe/asmr/`.