A New Approach for Measuring Complex Antenna Currents in a Vertical Array

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Overview

- This presentation is organized into five sections:
  1. Team Acknowledgement.
  2. Background and Existing Measurement Techniques.
  3. rvm (relative vector meter) – Using a VNA with specialized software to measure complex antenna current ratios.
  4. Applications of rvm.
  5. Summary.

1. Team Acknowledgement

- Paul Hubbard
- Paul Kiciak, N2PK
- Pete Michaelis, N8TR
- Tim Duffy, K3LR
- Jack Smith, K8ZOA
- Tom Lee, K8AZ

2. Background and Existing Measurement Techniques

- Why should we want to measure antenna currents?
- Antenna Modeling.
- Existing methods of measuring antenna currents.

Why should we want to measure antenna currents?

- We better care about EM radiation, or Amateur Radio doesn't exist.
- Accelerating charge on a wire produces EM radiation.
- Electric current is the flow of charge.
- An antenna element is any wire or conductor carrying RF current (planned or unplanned!).

Why should we want to measure antenna currents? (continued)

- A set of antenna elements creates an antenna array. The wire dimensions, orientation, and currents create the potential for gain and nulls in the overall antenna response pattern.
- Current is complex (vector), and usually expressed in terms of magnitude and angle.
- If we can measure the currents, we can ***insert*** them into an antenna model to obtain a high quality prediction of performance.

Antenna Modeling

- It's hard to imagine a contemporary antenna design project that doesn't include antenna modeling.
- A number of software packages exist that are based upon the NEC-2, NEC-4, or MININEC engines. (my examples will be EZNEC+ v5.0)
- I suspect that most all of us have spent **many** hours doing *what-if* analysis by varying wire size and placement and current source values.

Antenna Modeling (continued)

- Classic 80m 4-Square as an example (firing NE):

Wires

Wire Create Edit Other

☐ Coord Entry Mode ☐ Preserve Connections ☐ Show Wire Insulation

Wires

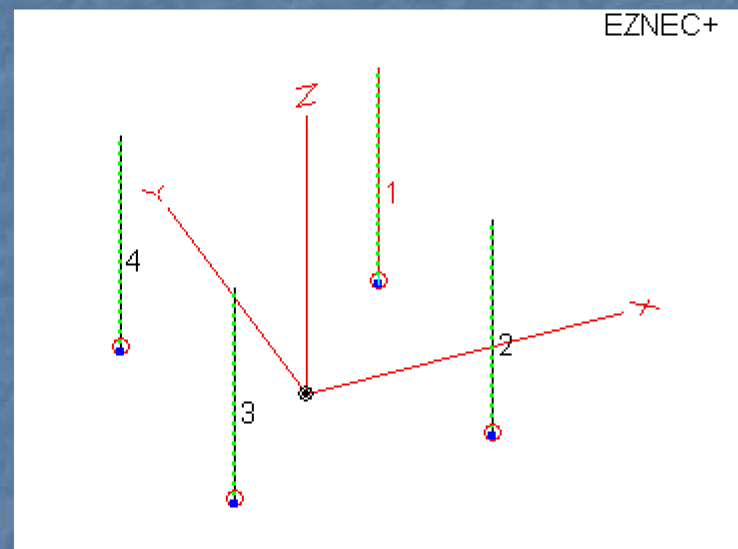
No.	End 1				End 2				Diameter	Segs
	X (ft)	Y (ft)	Z (ft)	Conn	X (ft)	Y (ft)	Z (ft)	Conn	(in)	
1	35	35	0	Ground	35	35	67.25		2	22
2	35	-35	0	Ground	35	-35	67.25		2	22
3	-35	-35	0	Ground	-35	-35	67.25		2	22
4	-35	35	0	Ground	-35	35	67.25		2	22

Sources

Source Edit

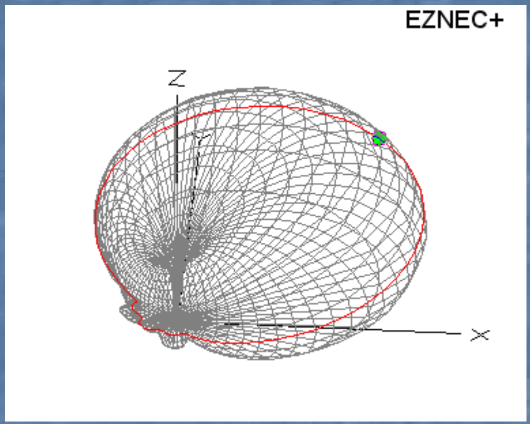
Sources

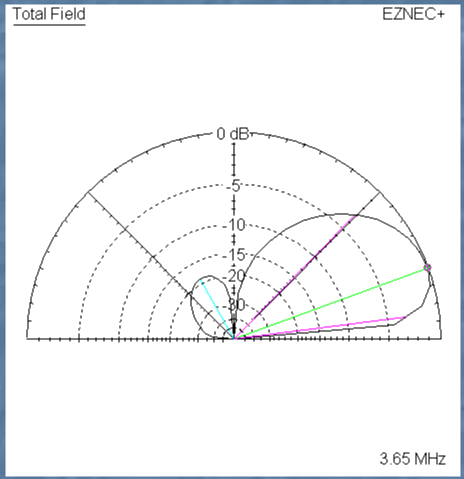
No.	Specified Pos.		Actual Pos.		Amplitude	Phase	Type
	Wire #	% From E1	% From E1	Seg	(V, A)	(deg.)	
1	1	0	2.27273	1	1	-90	I
2	2	0	2.27273	1	1	0	I
3	3	0	2.27273	1	1	90	I
4	4	0	2.27273	1	1	0	I

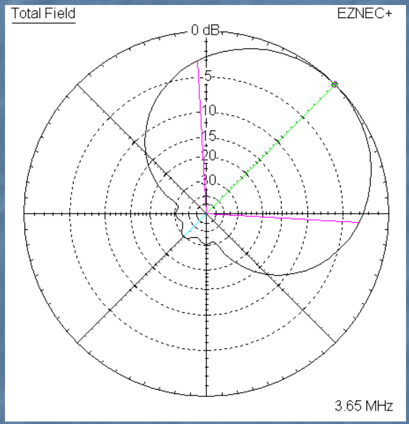


Other model inputs: ground type, ground characteristics, wire loss…

Antenna Modeling (continued)







- Graphical (pattern) and tabular results.
- In addition to the pattern, other important metrics include gain, F/B ratio, 3 dB beamwidth, RDF (or DMF), source impedance, and the take-off angle.

Antenna Modeling (continued)

- Although currents are specified as absolute values, the antenna gain and response pattern are a function of the *current ratios*, not absolute current values.
- Absolute current values are a function of applied power.
- Antenna performance is not a function of the power level.

Antenna Modeling (continued)

- There are infinite number of ways of specifying the same current ratios. These are equivalent.

	Source 1		Source 2		Source 3		Source 4	
Var.	Mag.	Angle	Mag.	Angle	Mag.	Angle	Mag.	Angle
1	1	-90	1	0	1	+90	1	0
2	2	-90	2	0	2	+90	2	0
3	1	0	1	+90	1	+180	1	+90
4	0.5	-180	0.5	-90	0.5	0	0.5	-90
5	12	+13	12	+103	12	+193	12	+103

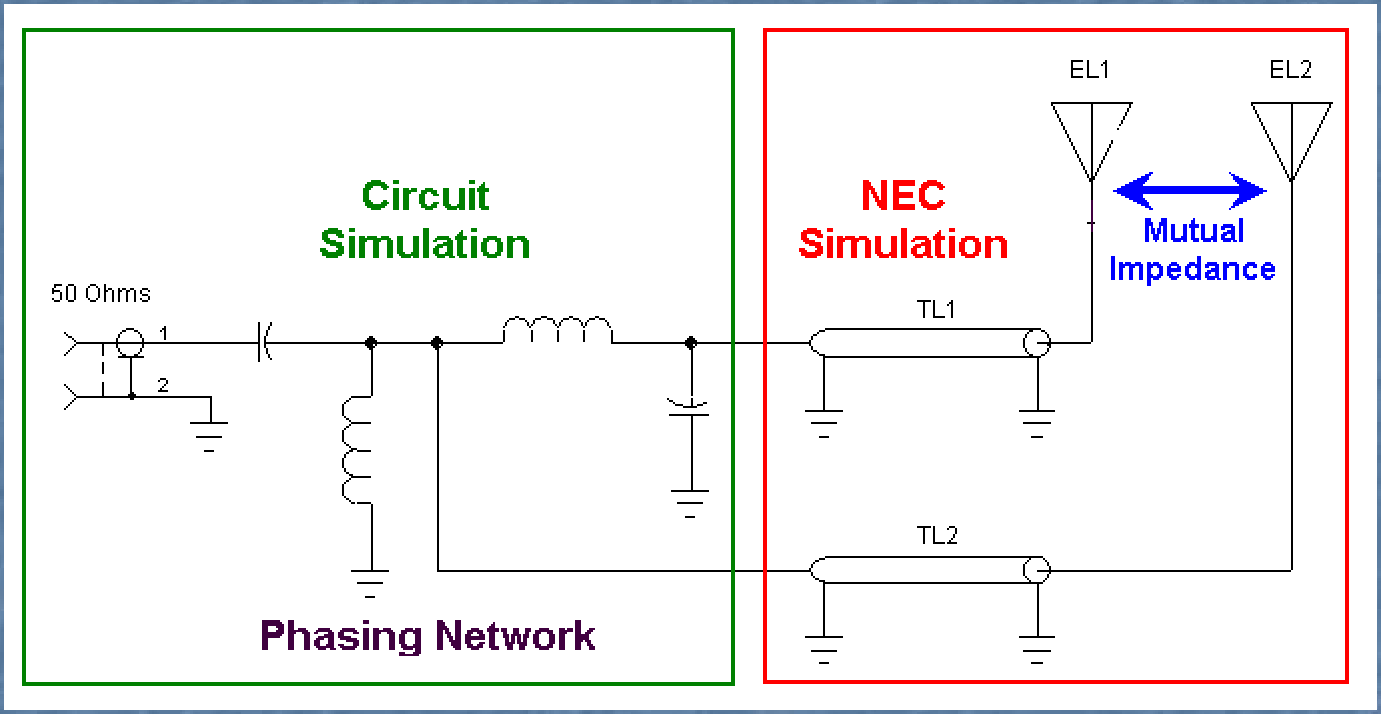
Antenna Modeling (continued)

- Modeling can be used for design before construction, **and** *evaluating actual performance* afterwards using measured currents. This is especially valuable when the frequency moves away from the target design frequency.
- Because the discrete phasing network is **not** part of the modeled array, it's behavior as a function of frequency is not taken into account.
- This is a general problem for all arrays with separate phasing networks built from discrete components.

Antenna Modeling (continued)

- If you hold the current sources constant (and ideal), and simply change the frequency, you are not accurately modeling the effect of the phasing network. This usually leads to overly optimistic results across the band.

Antenna Modeling (continued)



- Modeling both domains in a single environment is a difficult problem.

Antenna Modeling (continued)

- Some work has been done by others to model phasing networks in analog simulators such as flavors of *Spice*, and include the antenna elements as if they were lumped components, including mutual impedance. The challenge is creating antenna models that are accurate in the lumped domain. And, even if the networks are verified to produce the desired currents, the normal NEC outputs (patterns, gain, etc.) are not available since it's an analog simulator, not an antenna simulator.

Antenna Modeling (continued)

- Beginning with EZNEC v5.0, *insertion objects* and *virtual segments* make it possible to model most phasing networks. This capability could be quite powerful. More evaluation is needed to determine how closely completely modeled arrays track carefully measured arrays.
- Similar enhancements may be going on in other tools, but I am not aware of them.

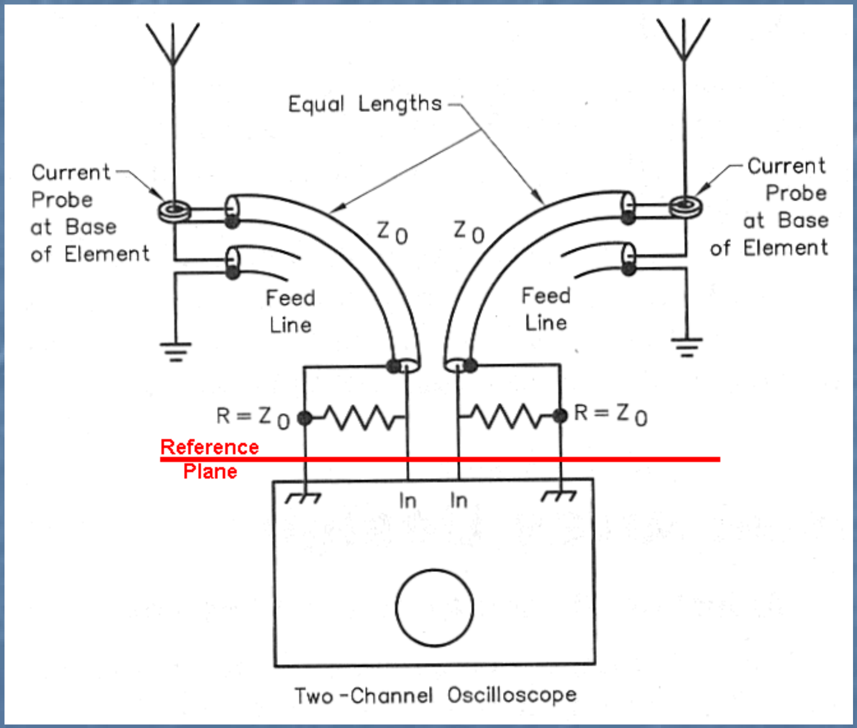
Existing methods of measuring antenna currents

- Sources of more information:
  - ARRL Antenna Book
  - ON4UN's Low-Band DXing
- Measuring magnitude is relatively easy – an RF ammeter.
- Some specific phase relationships, such as 90 degrees, invite use of quadrature phase detectors.
- A general purpose magnitude and phase measurement tool is the multi-channel oscilloscope.

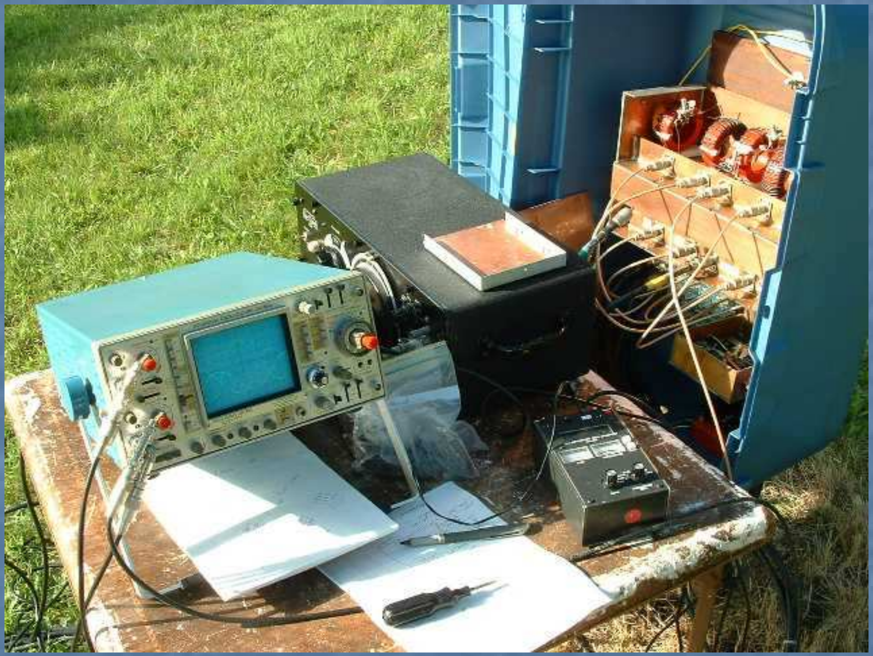
Existing methods of measuring antenna currents (continued)

- Current can be measured directly at the element feed points with current probes, or, indirectly measured as a complex voltage ¼ (3/4, 1 ¼, etc) wavelength from the feed point on a transmission line.
- Voltage measurement is a side-effect of *current forcing*.
- The voltage measurements *prefer* ideal transmission lines, at a single frequency, but can be more convenient to make.

Existing methods of measuring antenna currents (continued)

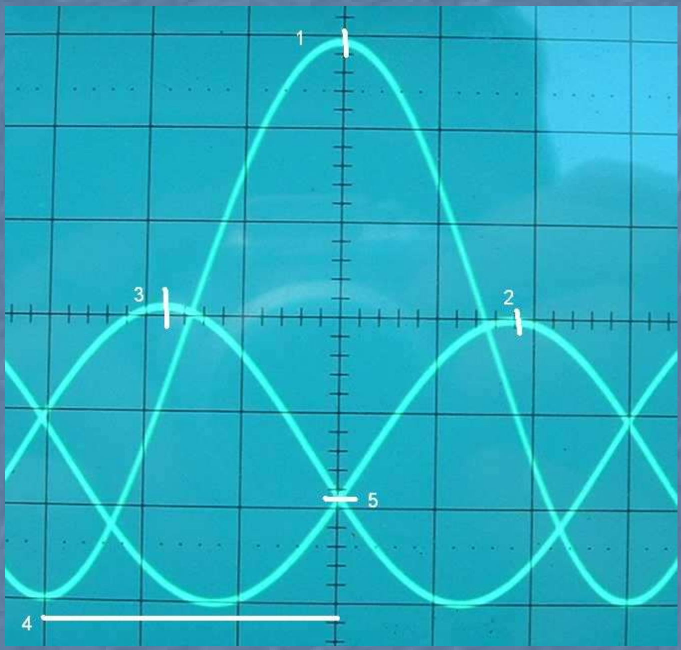


From ARRL Antenna Book, pg 8-30, 20th ed.

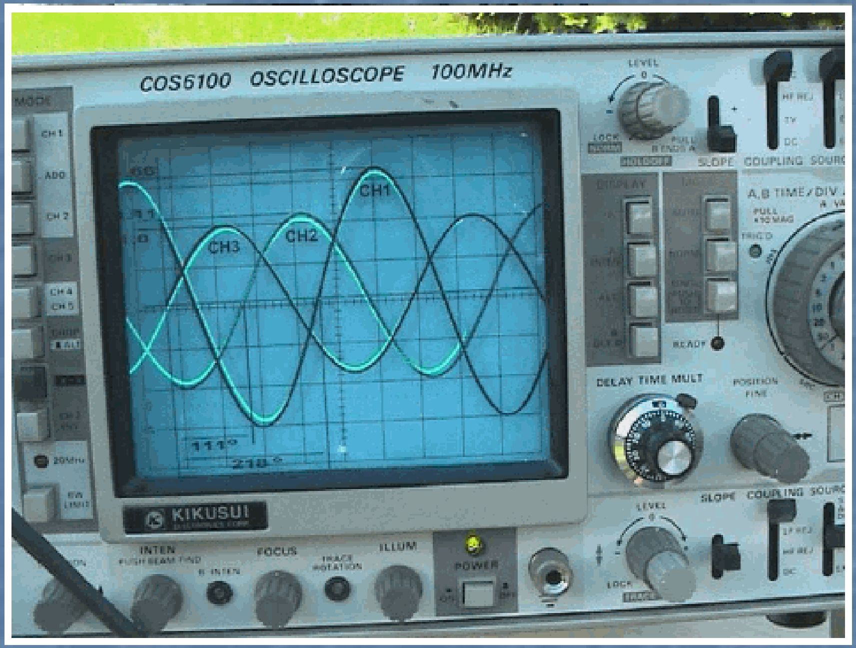


W8WWV Hex Array Field Adjustments

Existing methods of measuring antenna currents (continued)



W8WWV 40 m Hex Array



ON4UN 80 m 4-Square (2005 Dayton Antenna Forum presentation)

Existing methods of measuring antenna currents (continued)

- Q: Where is the reference plane?
- A: On the front panel of the scope.
- That means that the measurement will include the current probes and the test cables. This encourages that the probes and cables be identical so that they can be practically ignored.

Existing methods of measuring antenna currents (continued)

- Drawbacks to existing methods:
  - Tedious, cumbersome, usually single frequency analysis. Manual transcription of data. No direct tie to other analysis tools.
  - Scopes beyond two channels are more expensive and less common.
  - Reading the scope can be tricky, and the resolution is limited.
  - Scopes can require substantial AC power - outside.
  - Current probes and cables are above the reference plane, and will influence results if not identical. They are part of the Device Under Test (DUT).

rvm – Relative Vector Meter

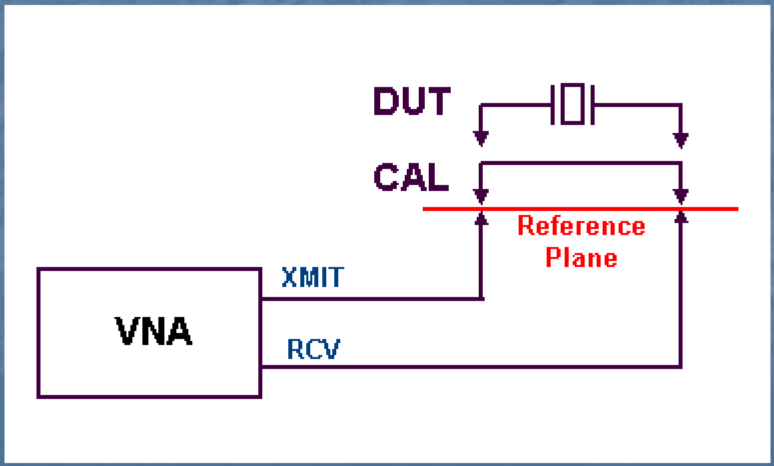
- Theory of Operation.
- Vectorscope.
- Frequency Scan.
- Measuring *Current Forcing.*
- Coupled Current Ratios.
- Power Port (dump power).
- NEC Driver.
- F/B Measurements.

rvm – Theory of Operation

- What is a VNA?
- Simply put, a transmitter and receiver in a box, where the receiver can produce both magnitude and phase information.
- A *transmission measurement* passes the transmitter signal through a Device Under Test (DUT) and the receiver detects the complex response.
- A calibration standard is used to provide a magnitude and phase reference. A *Through* in this case.

rvm – Theory of Operation

- Example: characterization of a crystal filter.
- The reference plane can be *extended* to include only the DUT, and not the cables and test jig.

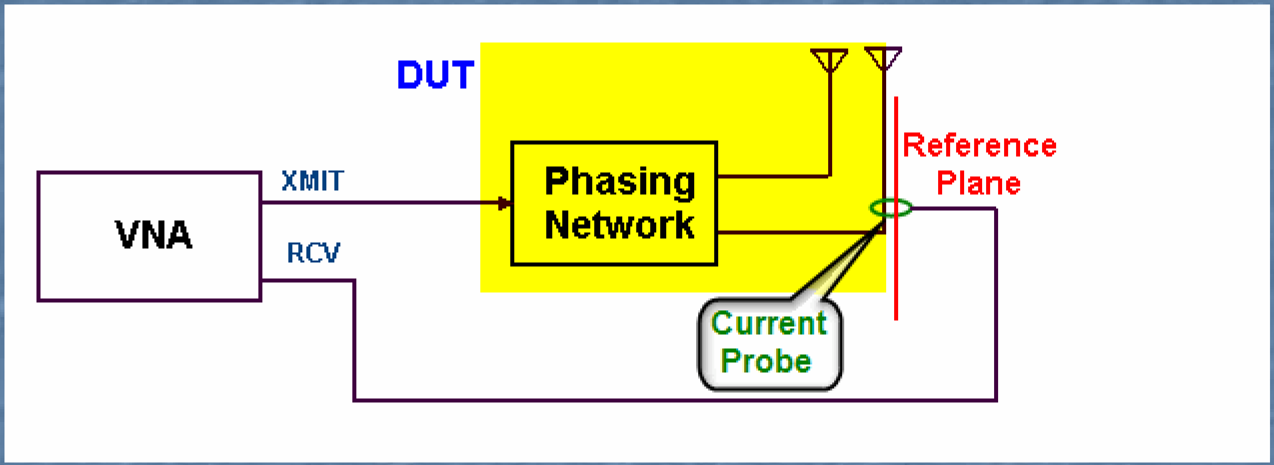


ICOM
Test
Jig

rvm – Theory of Operation

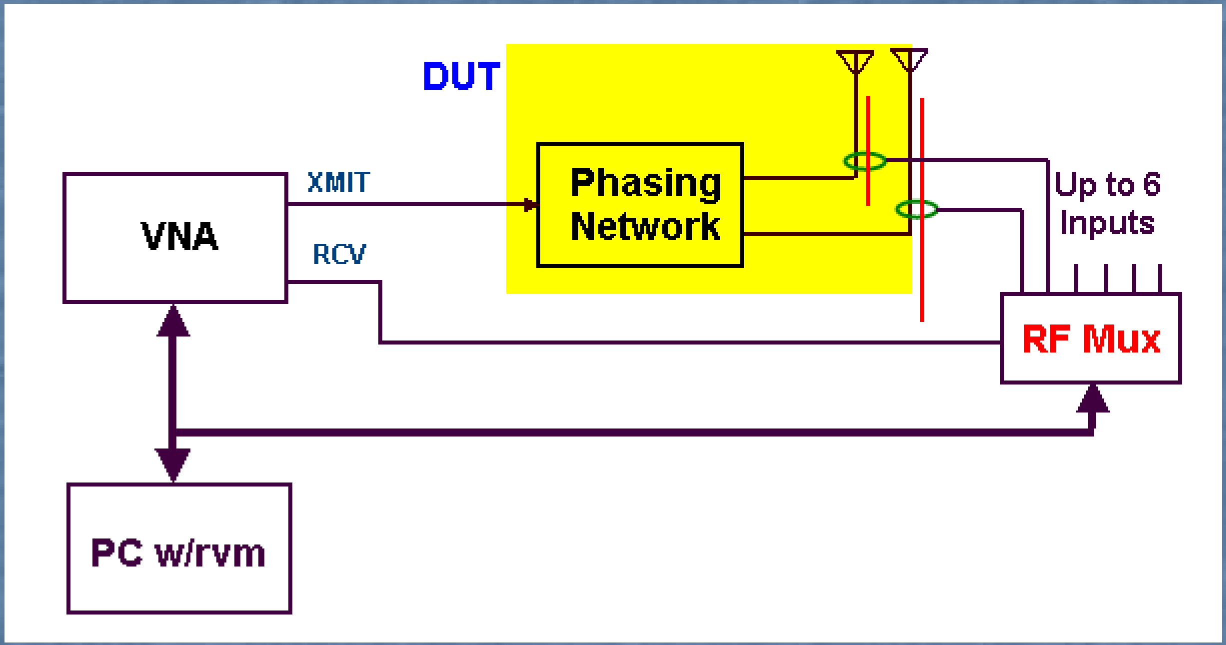
- Consider an entire phased array as a DUT, with a current measurement point at each element feed point.
- The primary of the current probe is part of the DUT, the secondary is within the reference plane.
- The current probes and cables are no longer part of the measured data (DUT).

rvm – Theory of Operation



- Add a computer-controlled hardware multiplexer to select current probes one after another.
- Choose a reference element, and divide all complex current values by it. The results are the antenna element current ratios relative to the reference.

rvm – Theory of Operation



- Calibration must be performed for each current probe. This is done once at the start of a session, and can be saved for future use if desired.

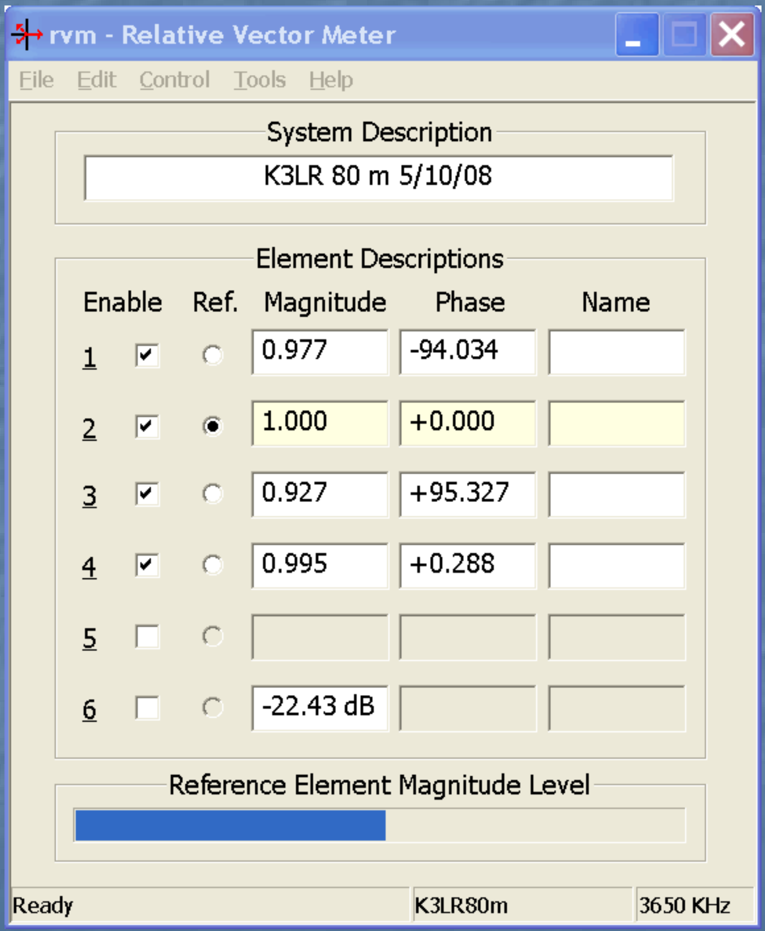
rvm – Theory of Operation

- The hardware multiplexer allows fully automatic measurement of up 6 elements. RF relays, 50 Ω
- Real time response for phasing network adjustment.
- It is desirable, but not required.

rvm – Theory of Operation

- Field Kart Unit 2000 (FKU2000)
  - Laptop w/sun shield
  - VNA
  - Multiplexer
  - Cables/Hardware
  - 12 V Tractor Bat.

rvm – Theory of Operation

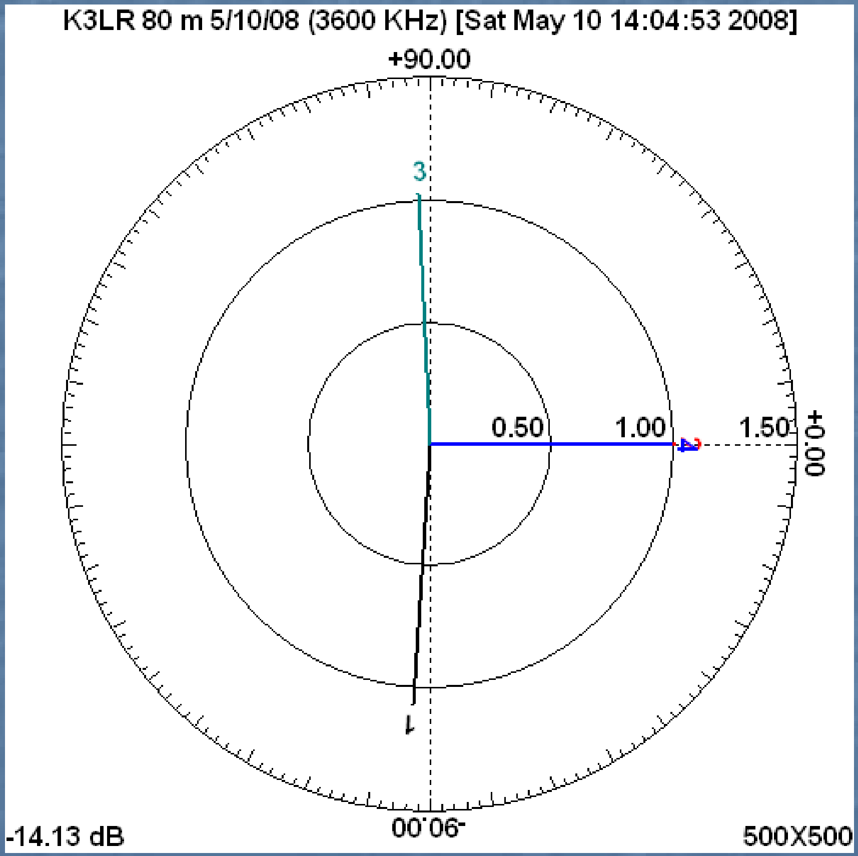


- rvm main window.
- Establishes the # of elements.
- Establishes the reference element.
- Establishes the reference current magnitude and phase.
- Launches other tools.

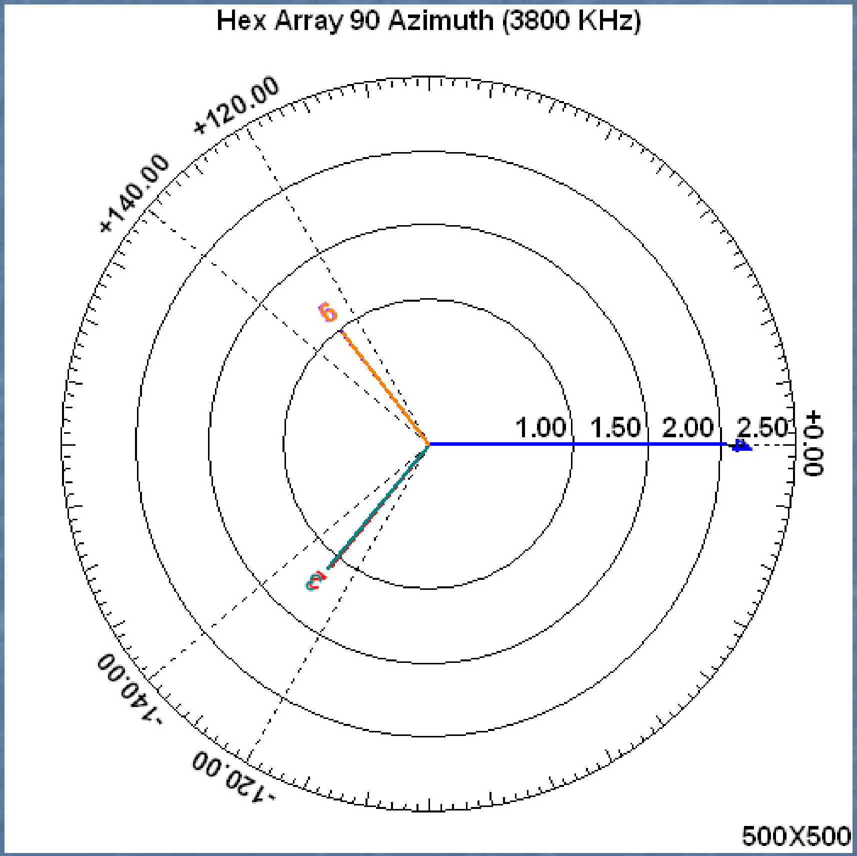
rvm – Vectorscope

- Used for real-time adjustment of phasing networks at a single target frequency.
- Polar representation of current vectors.
- User-defined current magnitude reference circles and phase angle reference lines.
- Requires the hardware multiplexer to be of practical value.
- Update rate: 5 to 10 Hz, depends upon # of elements.

rvm – Vectorscope (continued)



K3LR 80 m 4-Square NE

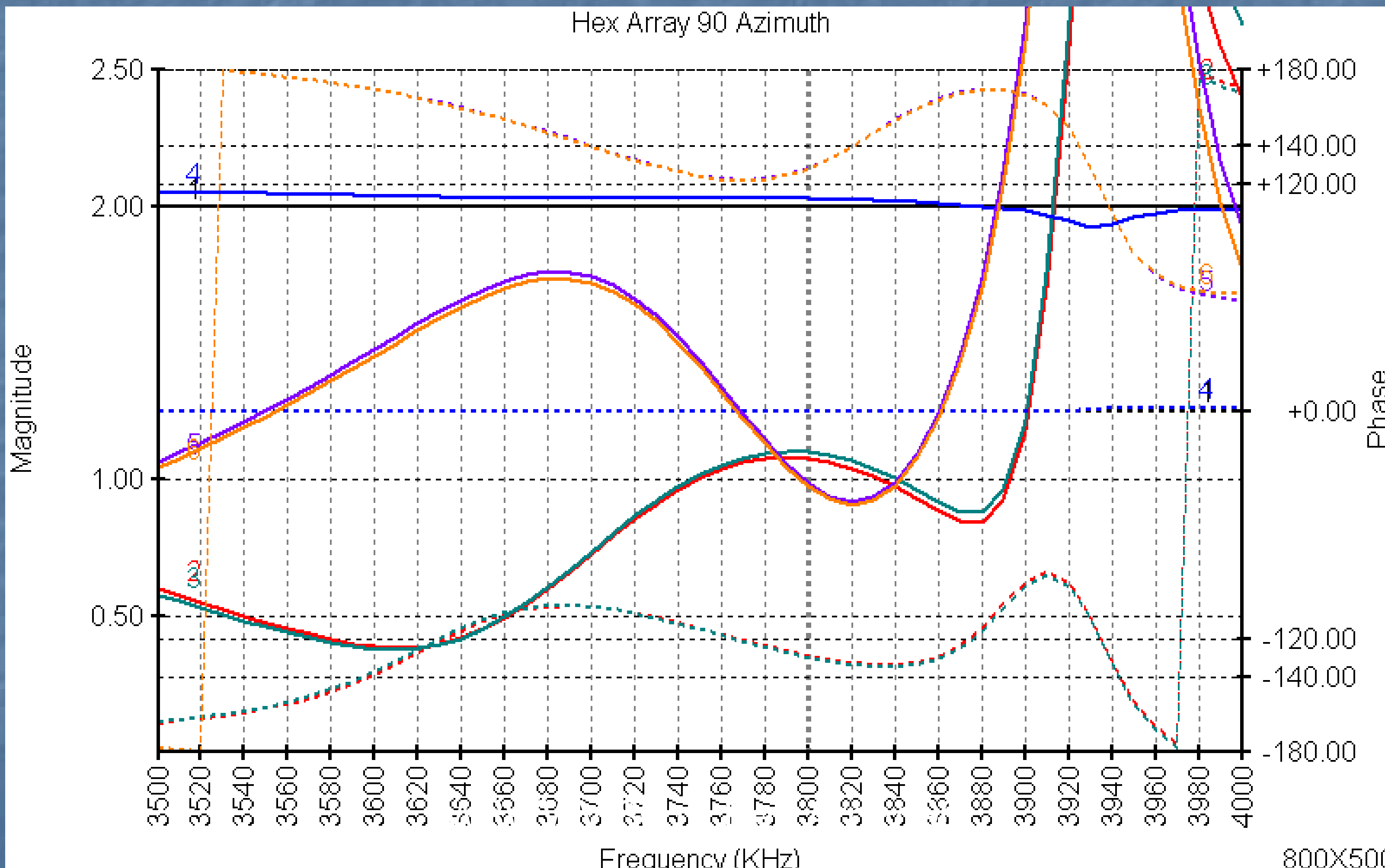


W8WWV 80 m Hex Array 90

rvm – Frequency Scan

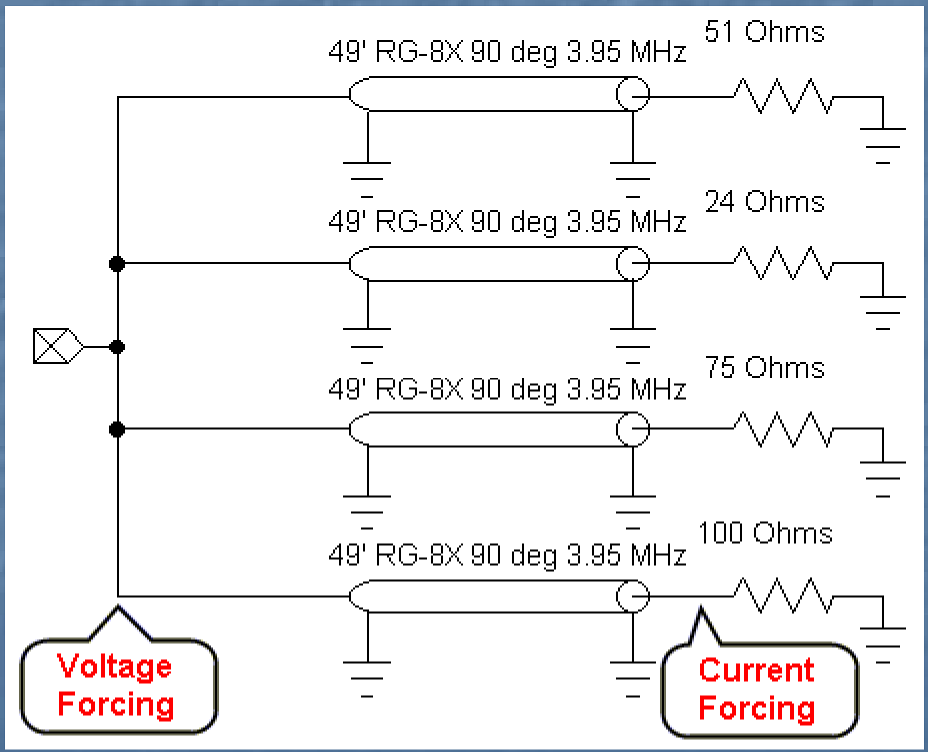
- Captures current magnitude and phase information across the entire test band, at a user-specified interval.
- User-defined magnitude and phase targets.
- Can display magnitudes, phases, or both.

rvm – Frequency Scan



rvm – Measuring Current Forcing

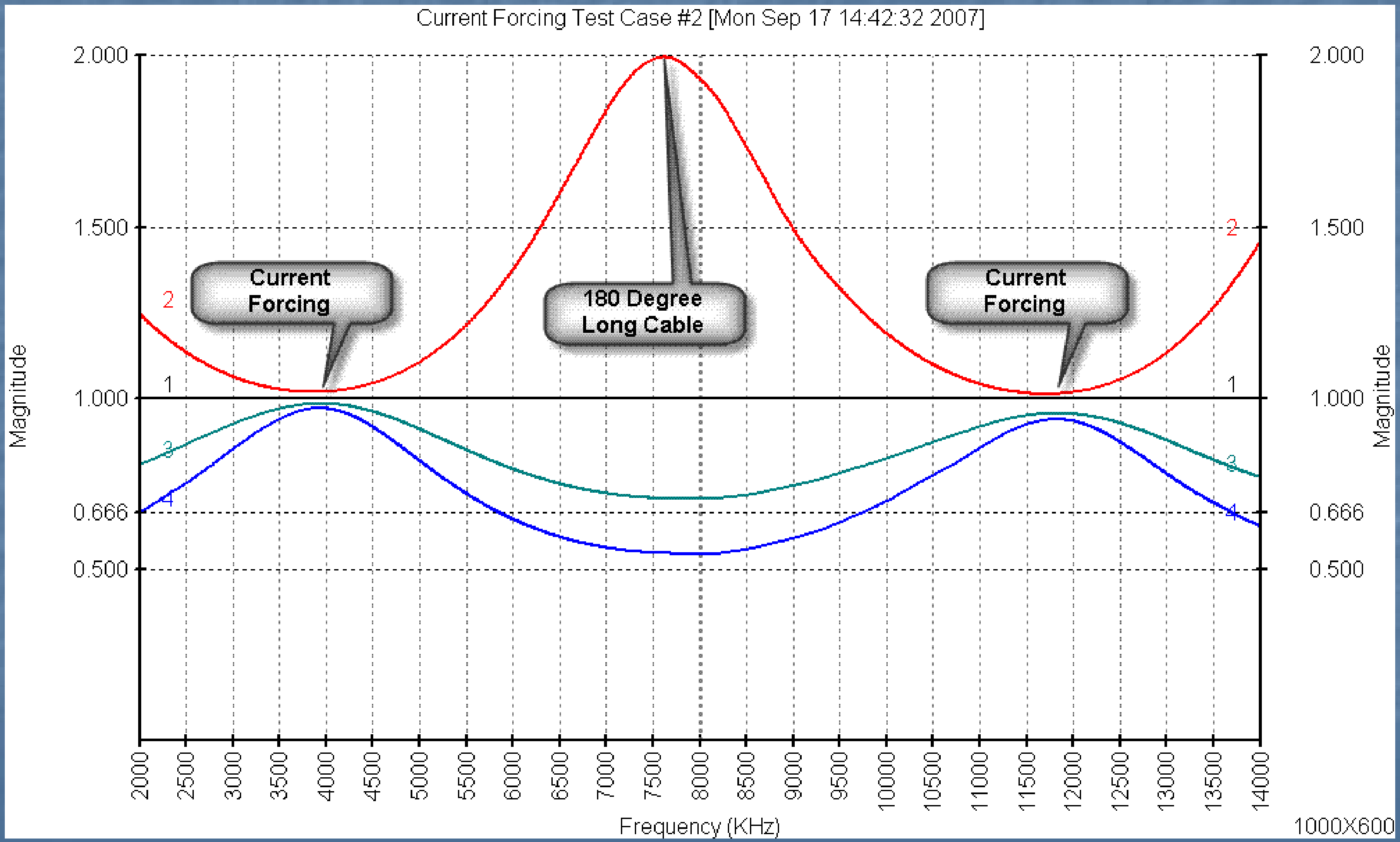
- The *current forcing* property can be easily demonstrated with rvm.



rvm – Measuring Current Forcing (continued)

- Assume 50 V & no transmission lines involved:
  1. 50 volts / 51 Ohms = 0.98 amps
  2. 50 volts / 24 Ohms = 2.08 amps
  3. 50 volts / 75 Ohms = 0.667 amps
  4. 50 volts / 100 Ohms = 0.50 amps
- Although these currents vary by a factor of 4, current forcing states they will be the same ¼ wavelength down the line.

rvm – Measuring Current Forcing (continued)



rvm – Measuring Current Forcing (continued)

- Deviations from equal currents are due to losses in the cable.
- Perfect current forcing *requires* ideal cables at one frequency.

rvm – Coupled Current Ratios

- The typical phasing network design process computes the *drive impedance* for each source.

$$Z_n = \frac{I_1 \times Z_{n1}}{I_n} + \frac{I_2 \times Z_{n2}}{I_n} + ... + \frac{I_n \times Z_{nn}}{I_n}$$

- Drive impedance is computed from *self-impedance* (Znn), *mutual impedance* (Zij), and *drive current* (In).
- Self-impedance is the impedance of an element in isolation. That's easy.

rvm – Coupled Current Ratios (continued)

- Drive current is our desired current. That's easy too (it's a *given*).
- Mutual impedance is the hard one. It can be computed from the self-impedance and the *coupled impedance*:

$$Z_{12} = \pm\sqrt{Z_{22} \times \left(Z_{11} - Z_{1,2}\right)}$$

rvm – Coupled Current Ratios (continued)

- The square root means that there are two solutions. In general, for element spacings of 0.15 to 0.7 wavelengths, the reactance is negative for the correct root.
- Still, this can be a source of error.
- Both Terman (2nd ed. 1937) and Gehrke (1983) provide a second method for computing mutual impedance.

rvm – Coupled Current Ratios (continued)

- Considering two elements at a time:

$$Z_{12} = -\frac{I_2 \times Z_{22}}{I_1}$$

- Where element 1 is driven, and element 2 is grounded. (it is *coupled* to ground)
- Note that I_2/I_1 is just a current ratio, and that is exactly what rvm is designed to measure!

rvm – Coupled Current Ratios (continued)

- rvm has a tool window that guides you through the process of measuring all pairs of coupled current ratios.
- The result is a table of data, for example:

```
Coupled Current Ratio Table (measured by rvm for 3680 KHz):
(1.000 @ 180.00°)     (0.538 @ 102.83°)    (0.589 @ 44.92°)     (0.574 @ 96.18°)
(0.534 @ 108.86°)     (1.000 @ 180.00°)    (0.585 @ 84.13°)     (0.589 @ 47.01°)
(0.351 @ 69.20°)      (0.590 @ 83.96°)     (1.000 @ 180.00°)    (0.620 @ 89.25°)
(0.547 @ 101.29°)     (0.556 @ 46.19°)     (0.586 @ 88.22°)     (1.000 @ 180.00°)
```

- Each value is –I2/I1 (column, row).

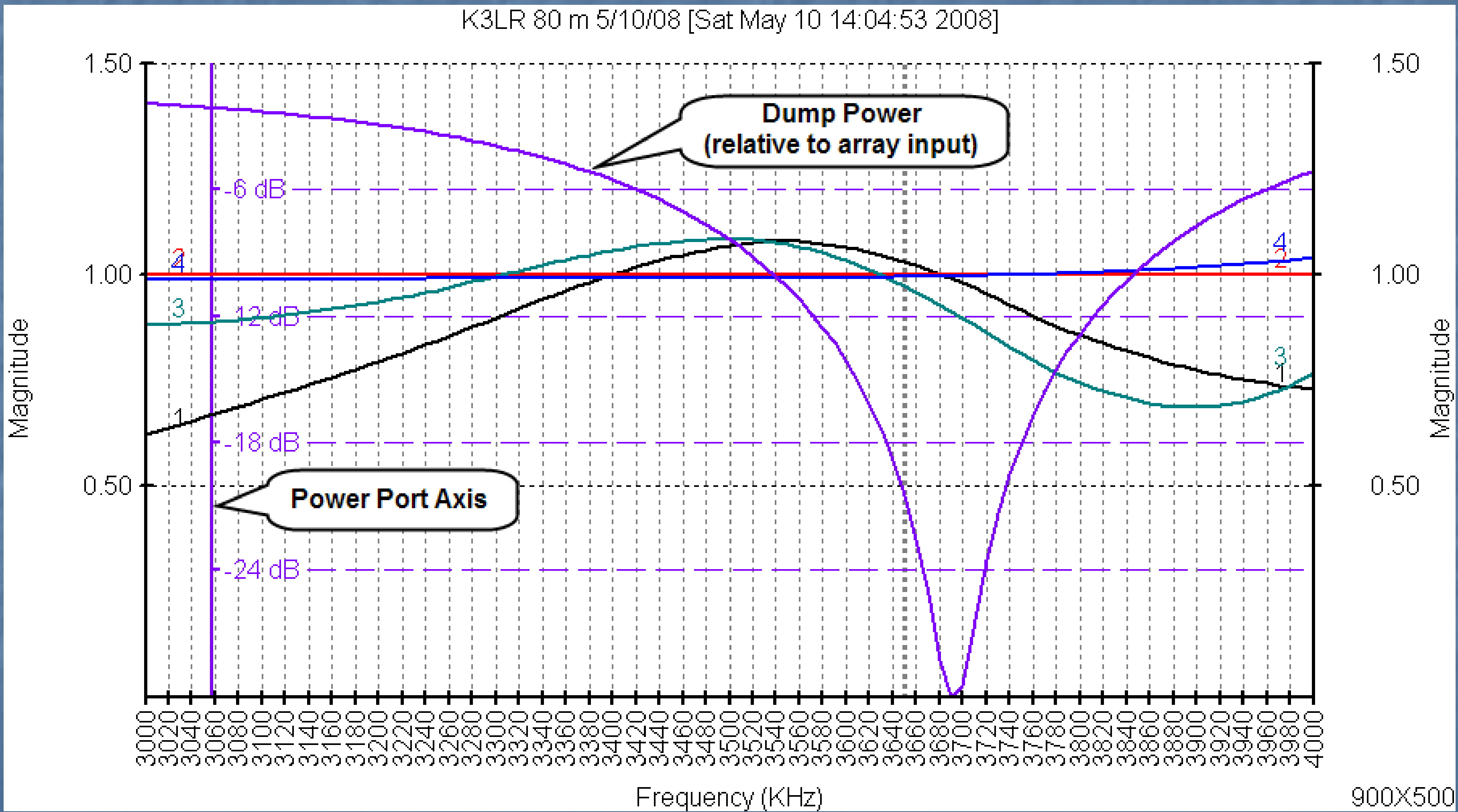
rvm – Coupled Current Ratios (continued)

- This current ratio data can be combined with self-impedance data to compute the mutual impedance for each pair.
- For a 4-element case computed using both methods, the maximum error was 1.4%.
- Coupled current ratios from rvm can be used to either determine, or, confirm mutual impedance computed by other methods.

rvm – Power Port

- A popular phasing network, the *4-Square hybrid coupler*, terminates the *isolated port* with a 50 Ohm dummy load.
- Power at this port represents power dumped and not radiated.
- Since rvm is nothing more than a VNA making transmission measurements with a front-end multiplexer, we can use a channel to monitor the power being dumped to the dummy load.

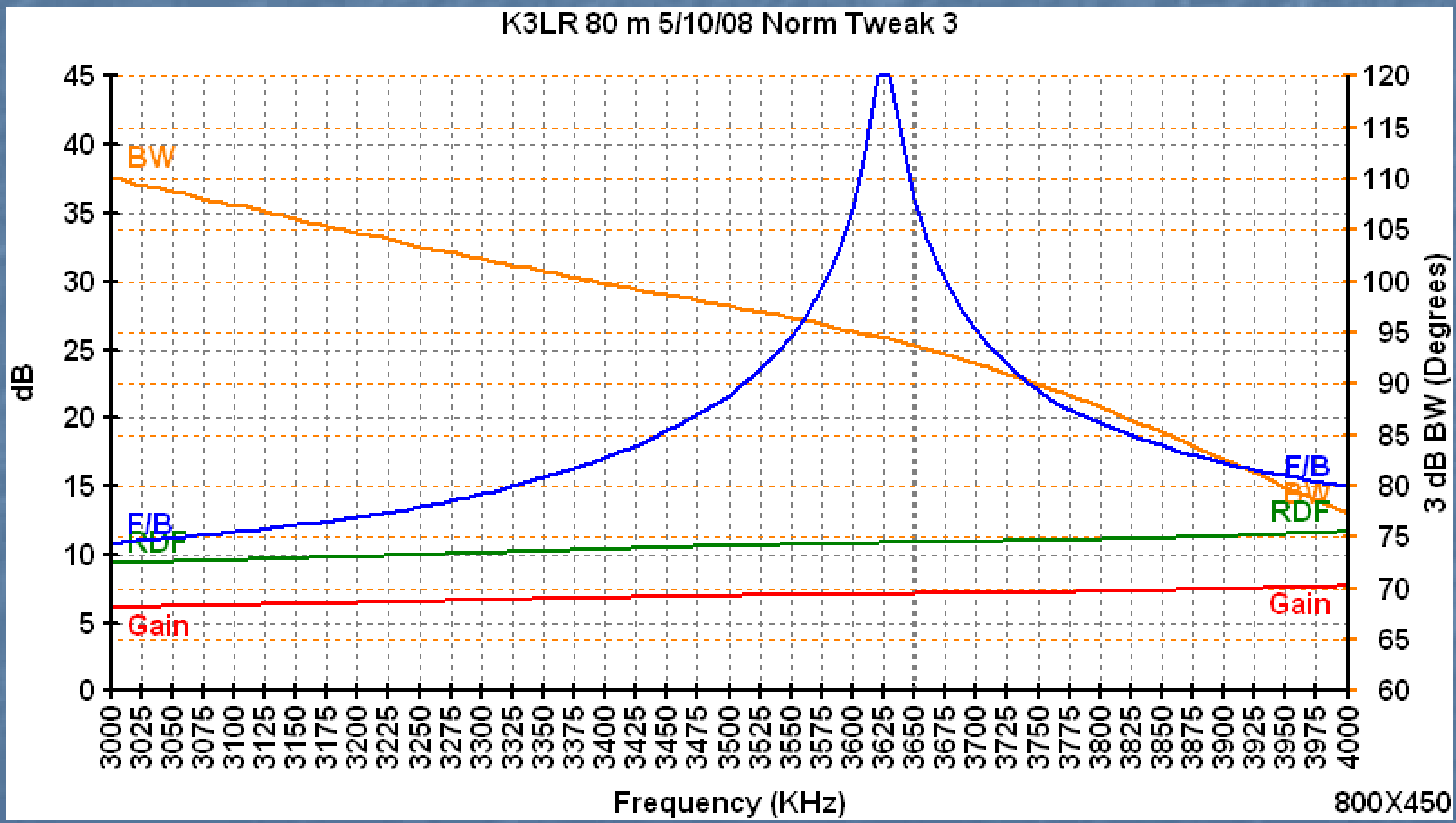
rvm – Power Port



rvm – NEC Driver

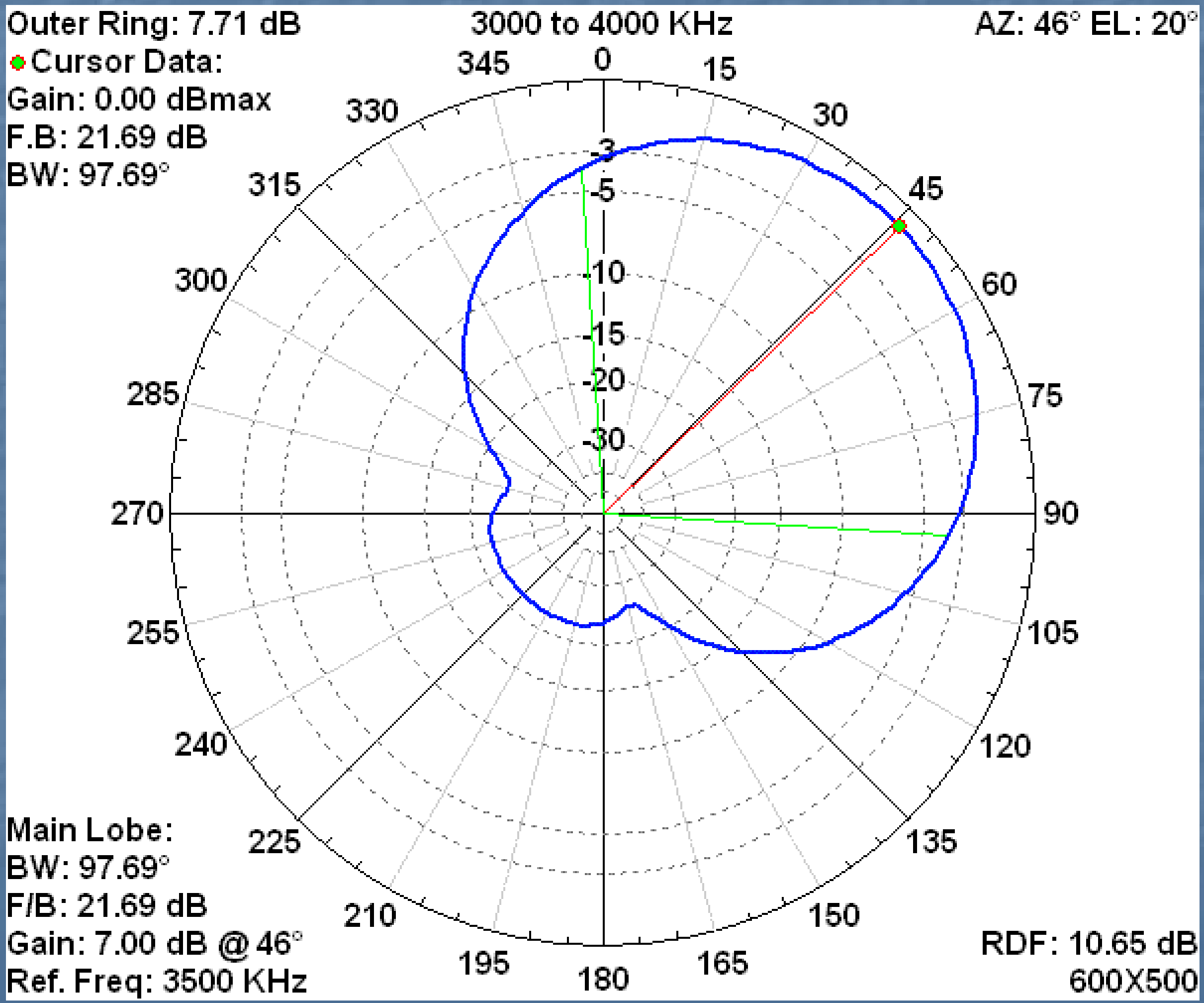
- The complex current data measured by rvm can be entered into the current sources in a NEC model and then analyzed to predict performance.
- Typical frequency scans can consist of 50 to 100 frequency points. That's a lot of data!
- Entering all of this data, running the NEC engine, and then analyzing the results can be tedious, time consuming, and error prone.
- The rvm NEC Driver automatically generates (edits) the models, runs the engine, and then collects all output for a single unified graphical and pattern analysis.

rvm – NEC Driver



NEC Driver Graph of Collected Model Data

rvm – NEC Driver



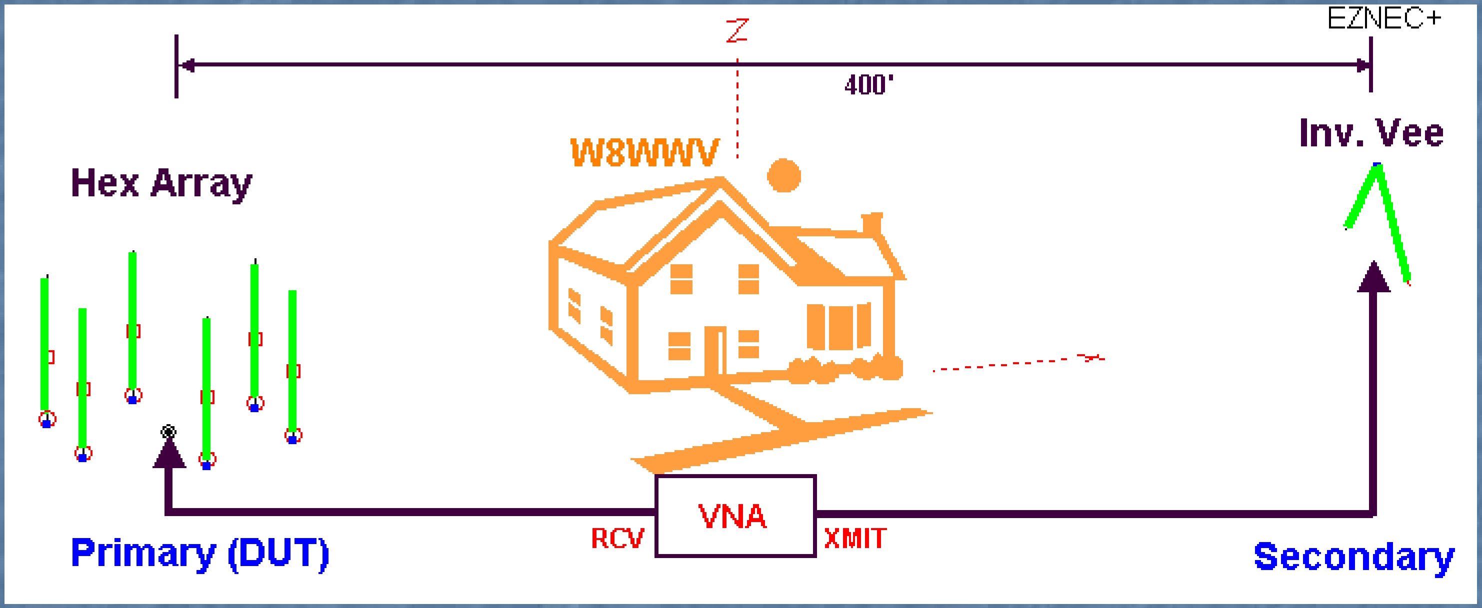
rvm – F/B Measurements

- It's always a wise idea to independently verify results whenever possible.
- Antenna gain, RDF, and beamwidth are relatively hard to measure, and tend to change slowly across the band.
- F/B, however, usually has a very distinct *signature* across the band.
- F/B can be measured relatively easily.

rvm – F/B Measurements

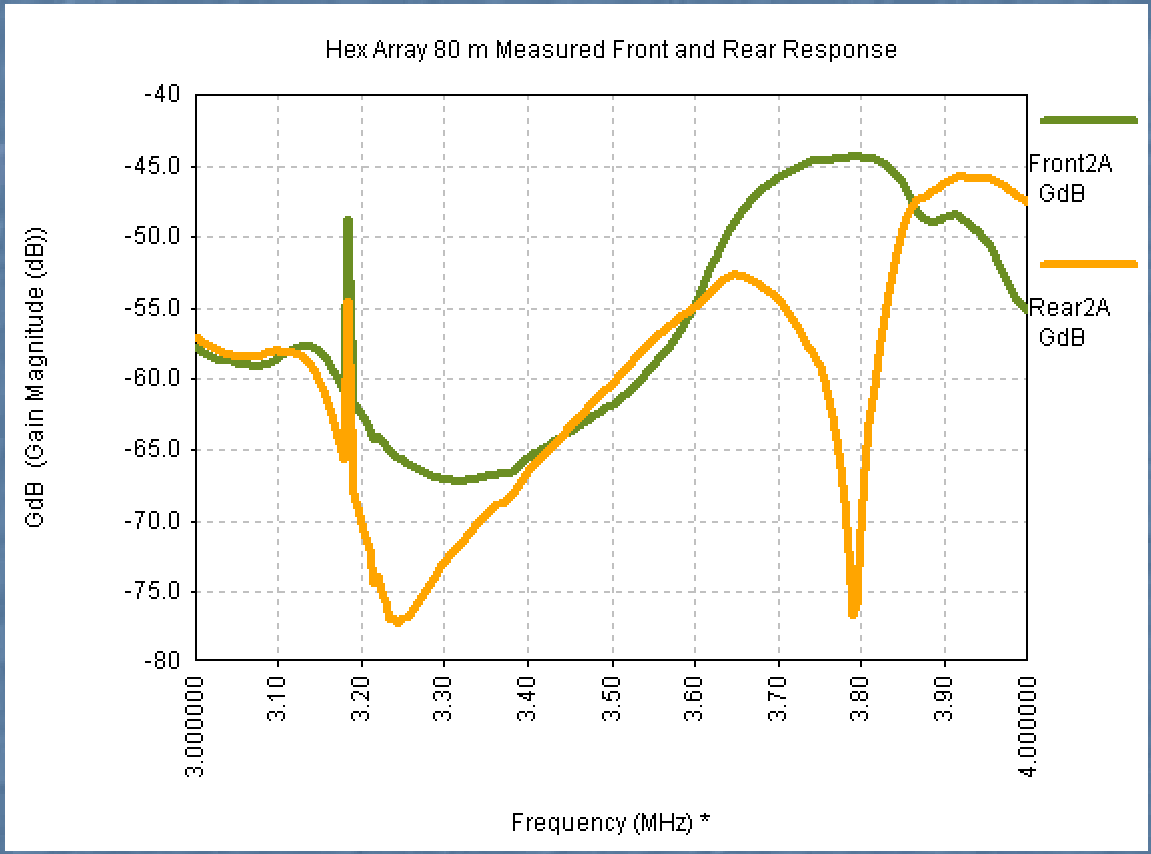
- With a fixed, electrically rotatable array, we usually compare the front response of one direction to the rear response of the opposite direction. For a symmetric array, this is the F/B.
- This allows the secondary antenna to stay at a fixed location, as opposed to moving to the opposite side of the array. It's easier!
- Although the response of the secondary antenna is measured, it is *subtracted out* in the comparison.

rvm – F/B Measurements



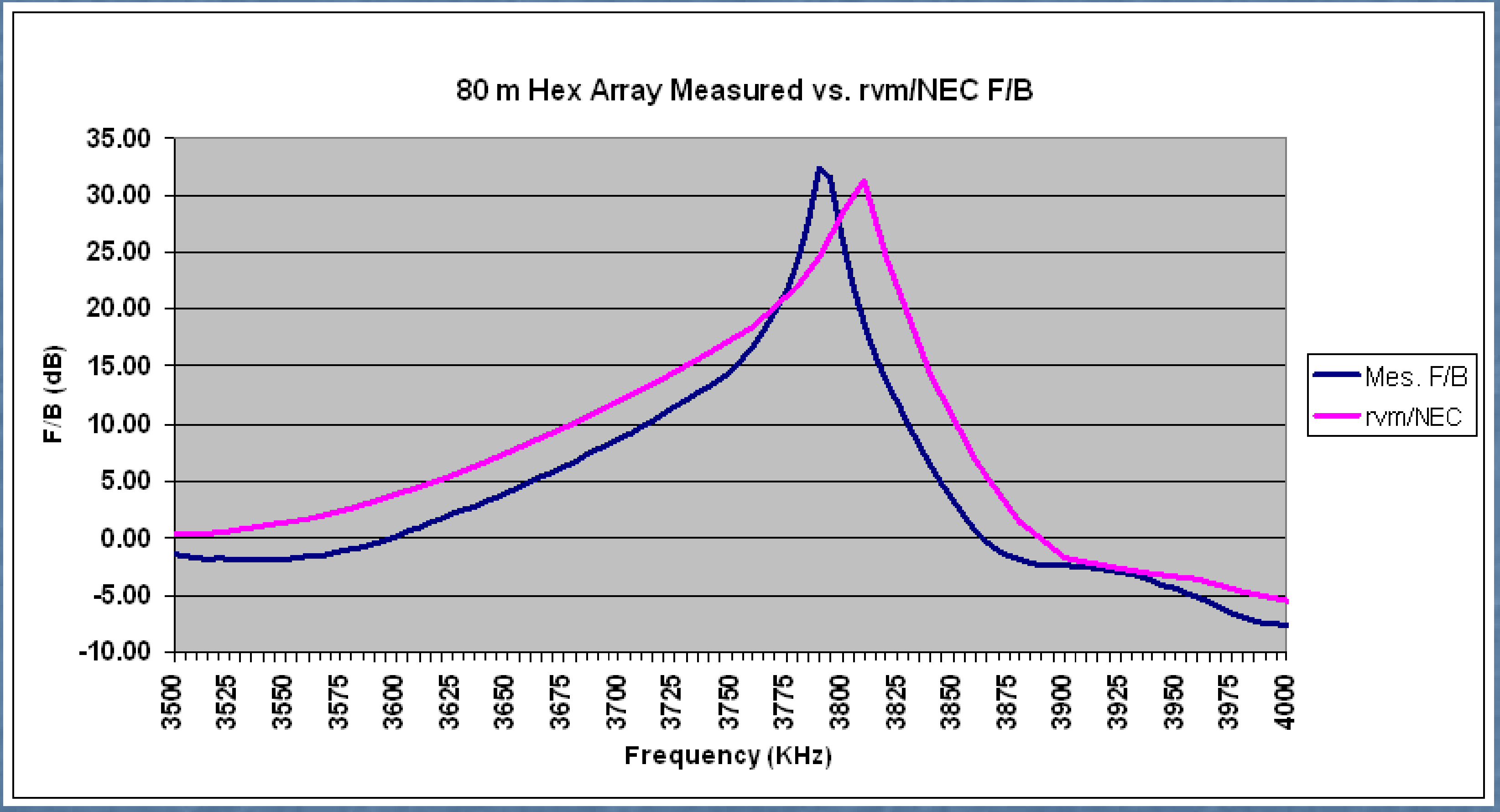
- The separation is only 400′, and the alignment is a little off. Not the best antenna test range for 80 meters!
- Use the VNA to make a funny form of transmission measurement.

rvm – F/B Measurements



- Front is the 90° response, Rear is the 270°.

rvm – F/B Measurements

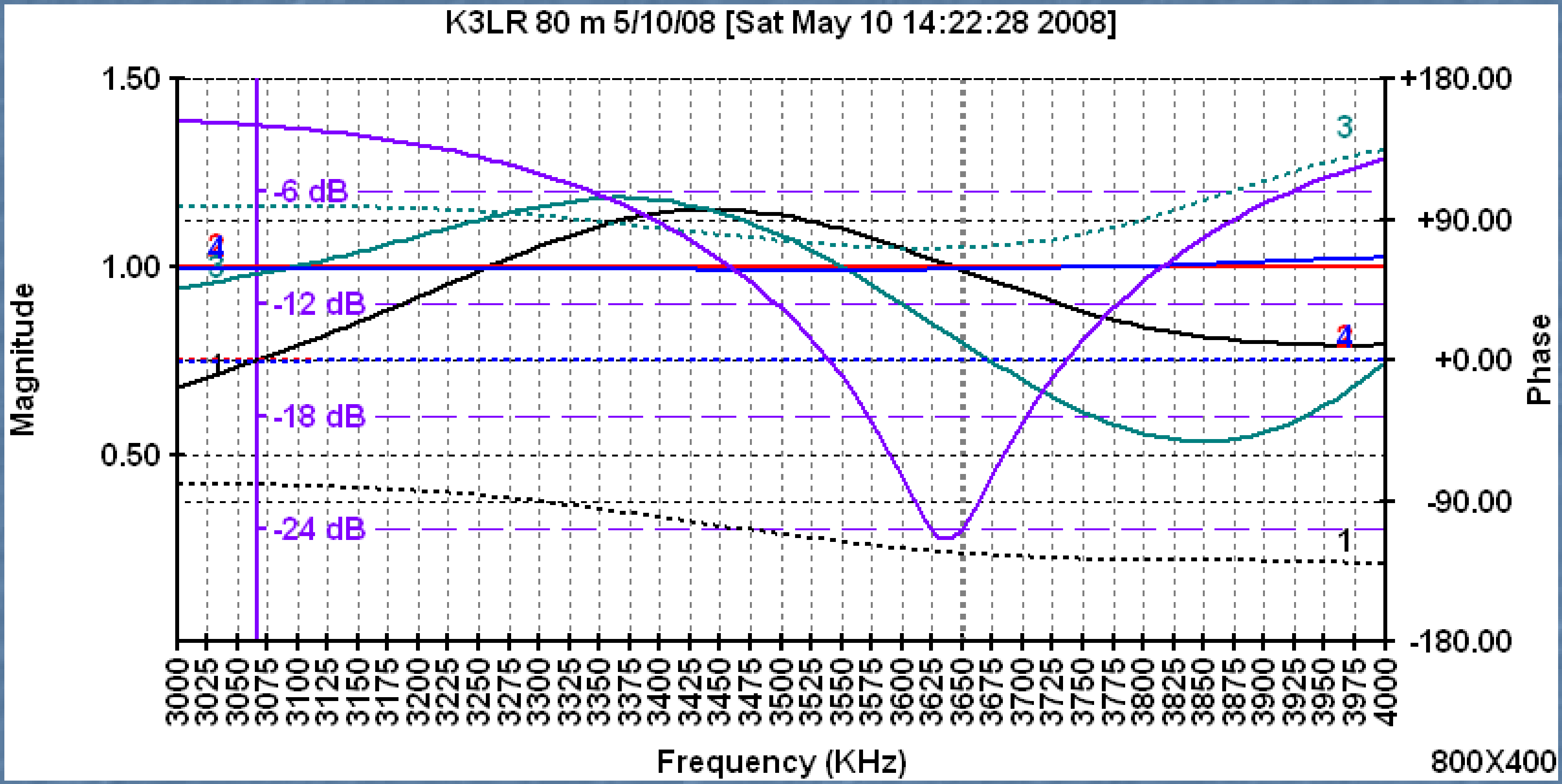


- Very good agreement for a very informal setup.

4. Applications

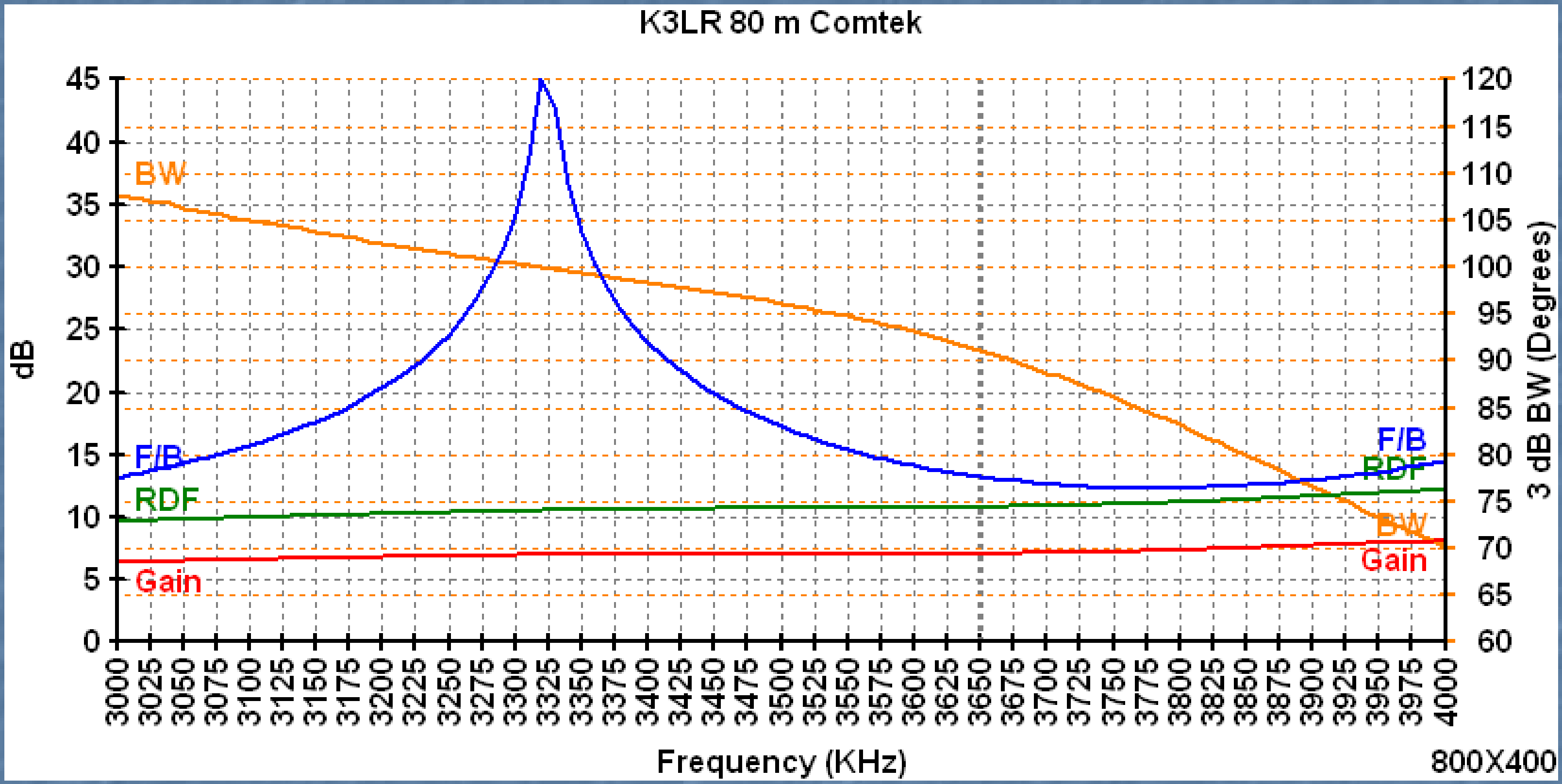
- Using rvm for exploration and answering some questions.
  - What does an analysis of the K3LR 80 m 4-Square tell us?
  - What performance is available with other phasing network design approaches?
  - Beauty is in the eye of the beholder.

Applications



- 80 m Comtek network current measurements.

Applications



- Performance implied by transferring currents to NEC models (elevation is that of maximum gain, 20°).

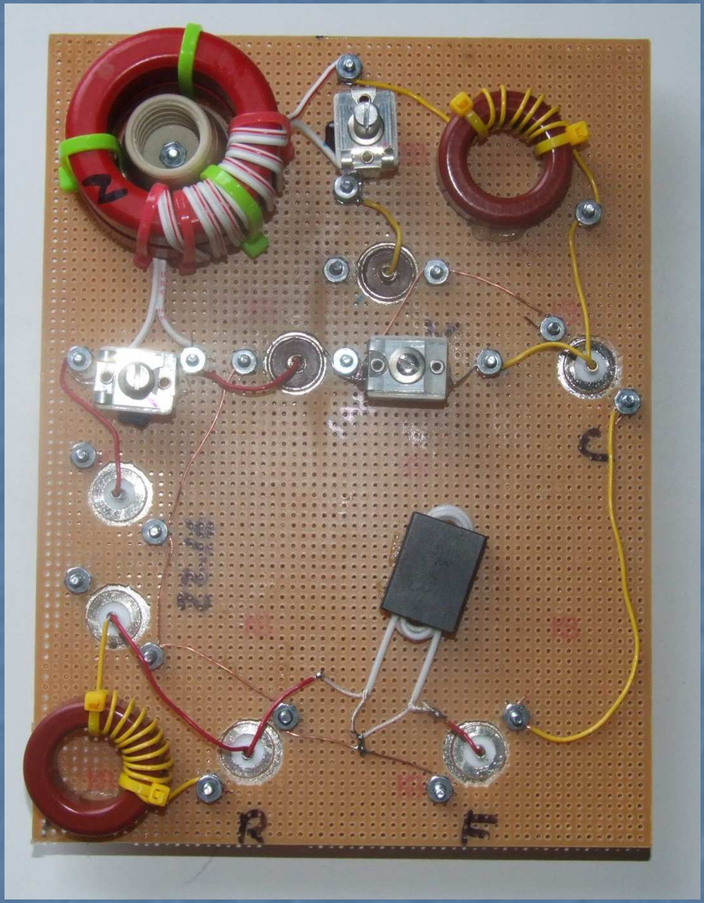
Applications

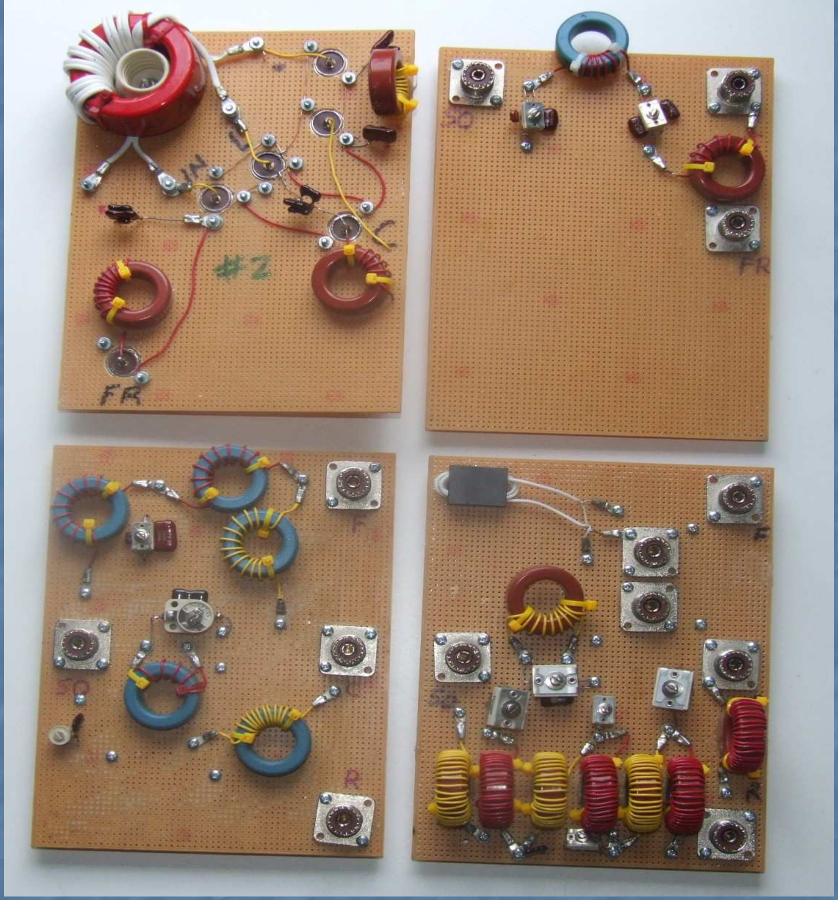
- We decided to build a series of trial phasing networks following the popular design approaches.
- Evaluate each for performance, especially across the contest/DX portion of the band (3500 – 3800 KHz).
- Not a detailed analysis of the classic hybrid coupler phasing network (yet).

Applications

- Phasing Network design approaches:
  - Standard Comtek (hybrid coupler, 180 trans.)
  - Simplest (Lahlum with 180 trans., or coax)
  - Pure Lahlum (W1MK)
  - Crossfire (W8JI)
  - Port Matched Hybrid Coupler
- All design/implementation errors are mine! Approaches taken from the 4th ed. ON4UN

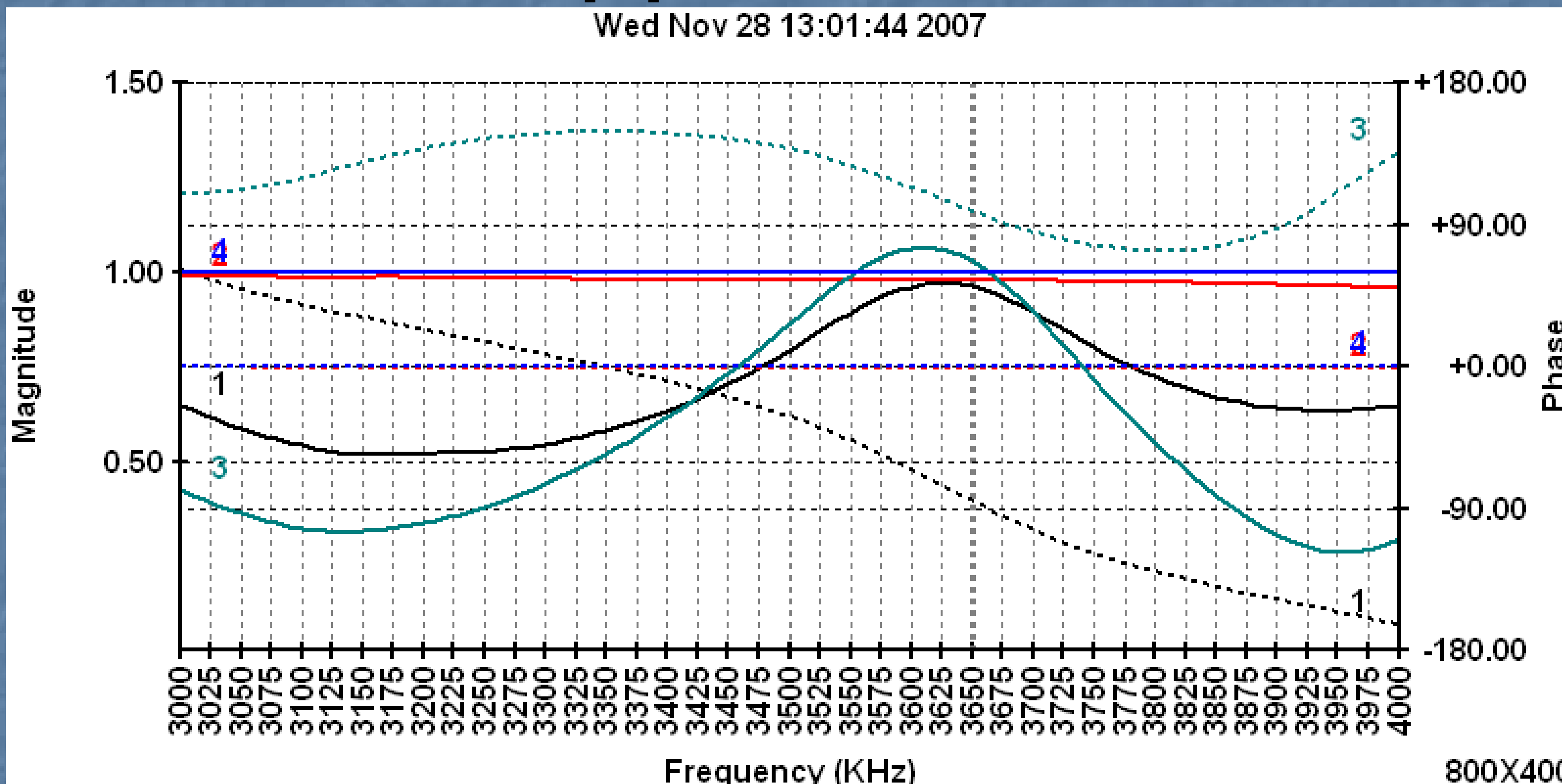
Applications





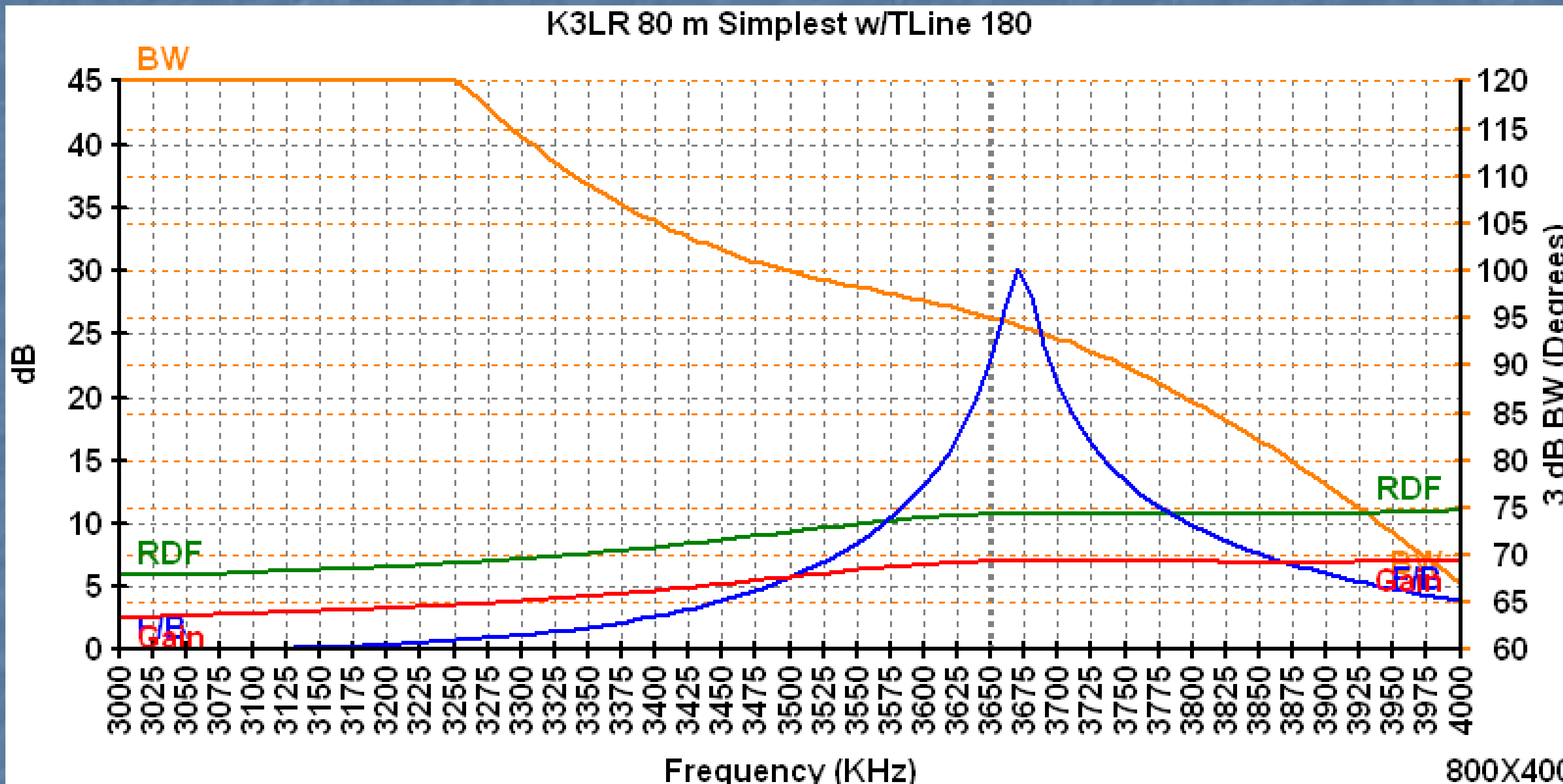
- Standard construction using double layer of perfboard, trimmers & silver mica caps, and inductors wound on #2 (or #1) iron cores.

Applications



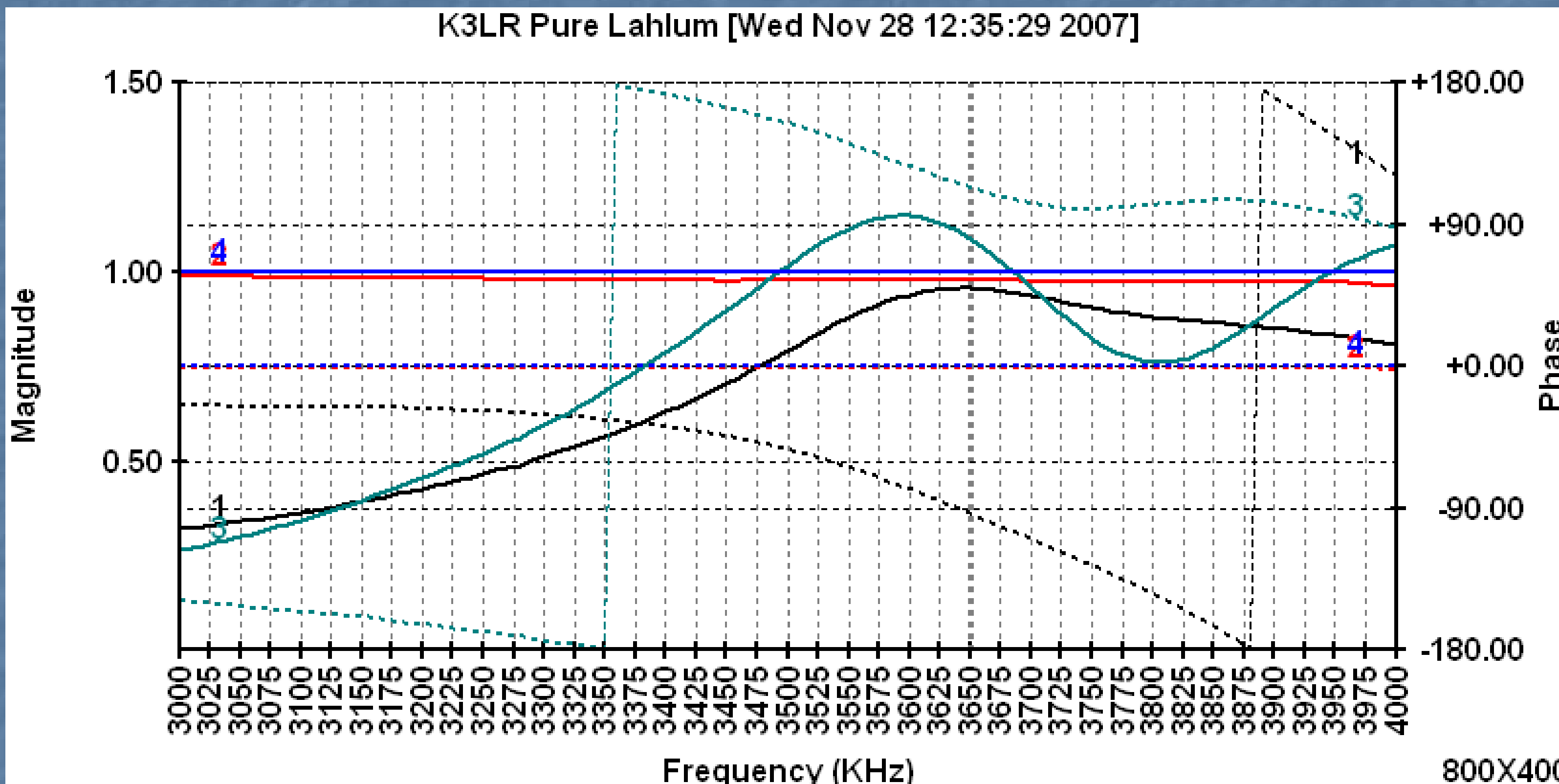
- Simplest, using 180° TLine to derive Front from Rear.

Applications



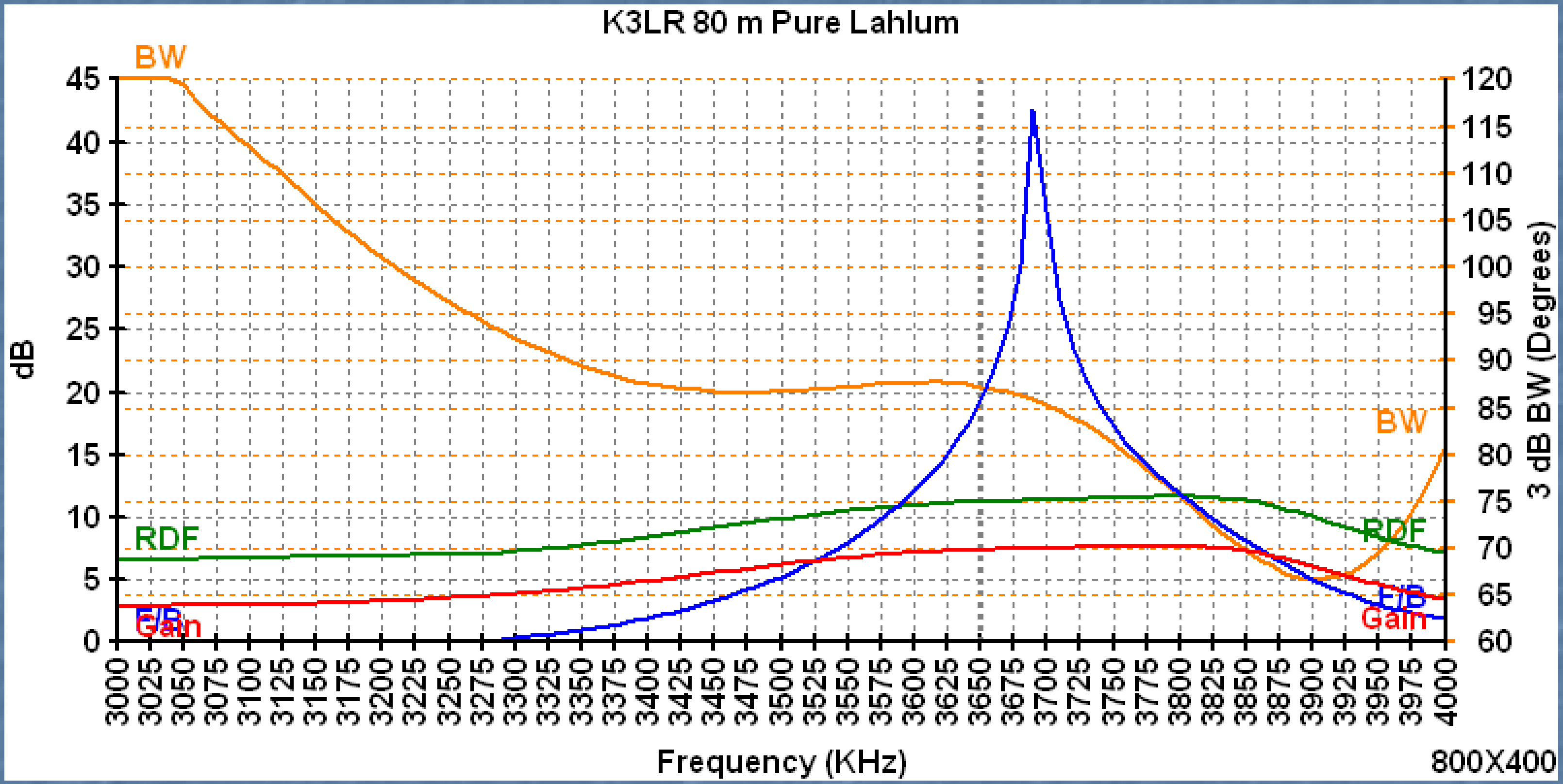
- Simplest w/TLine performance.

Applications



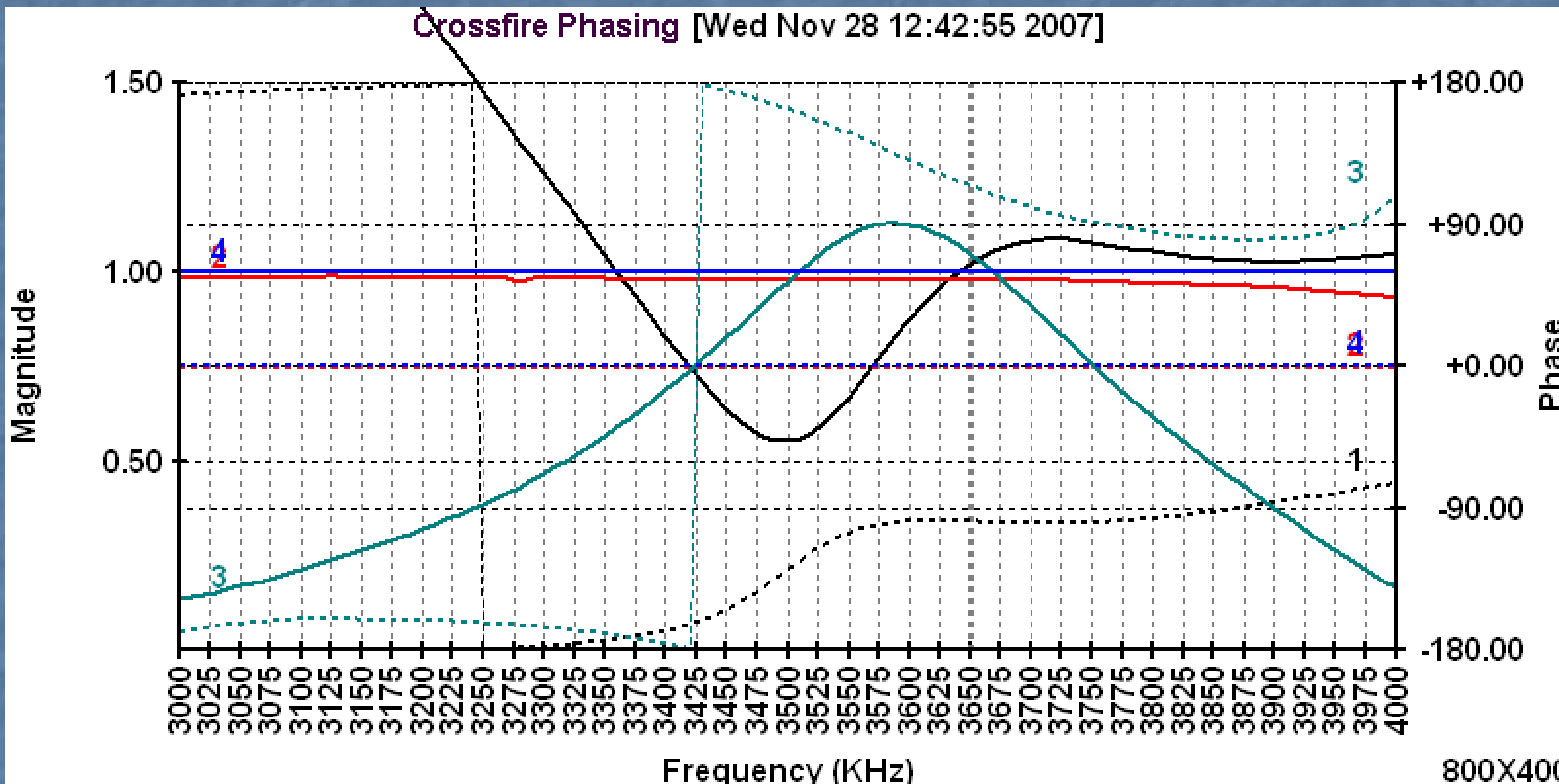
- Pure Lahlum – use L networks for 2 of the 3 legs. Phase targets were +- 103 degrees, not 90.

Applications



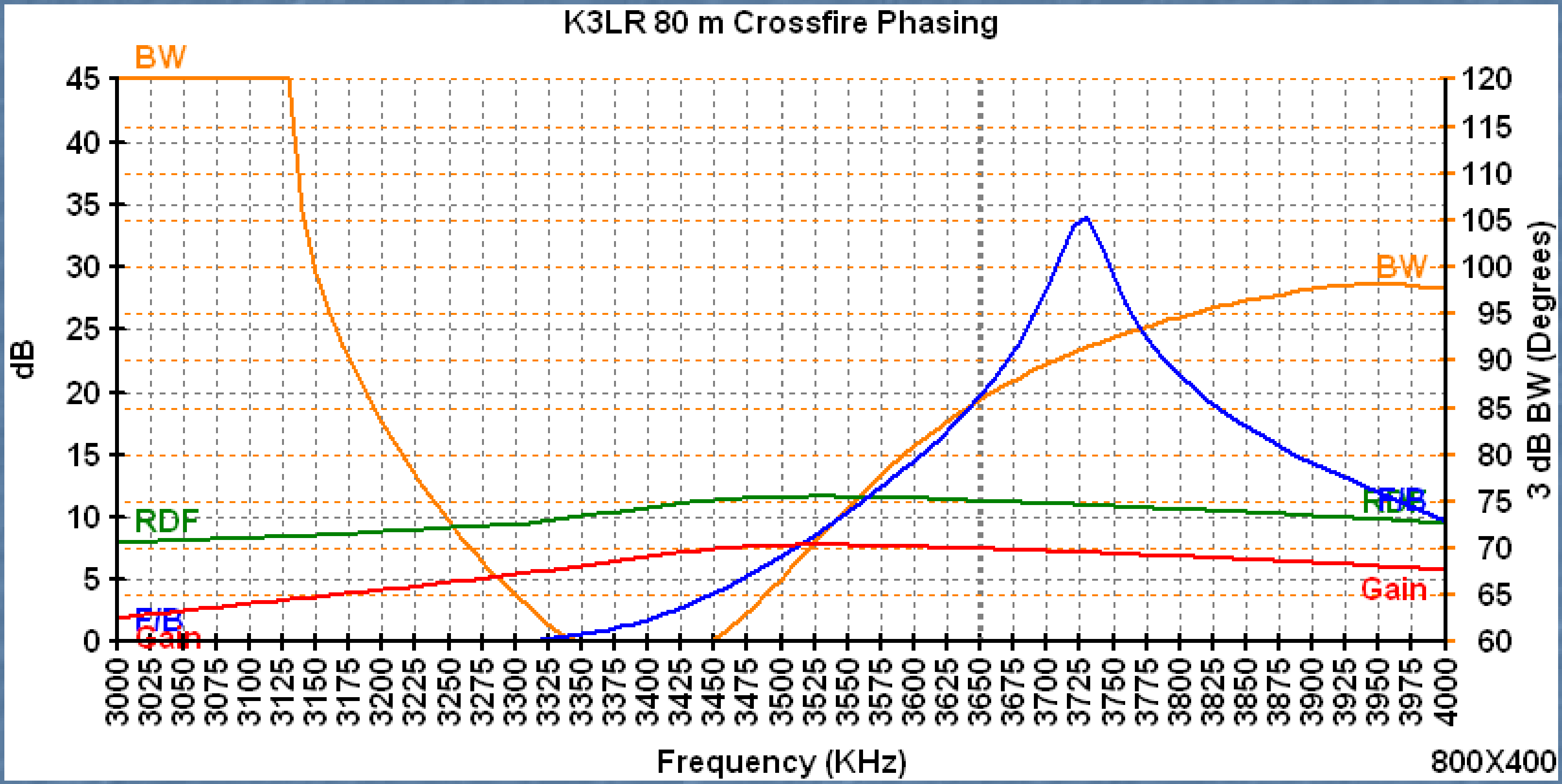
- Pure Lahlum performance.

Applications



- Crossfire Phasing, artificial TLine. Phase targets were +- 103°.

Applications

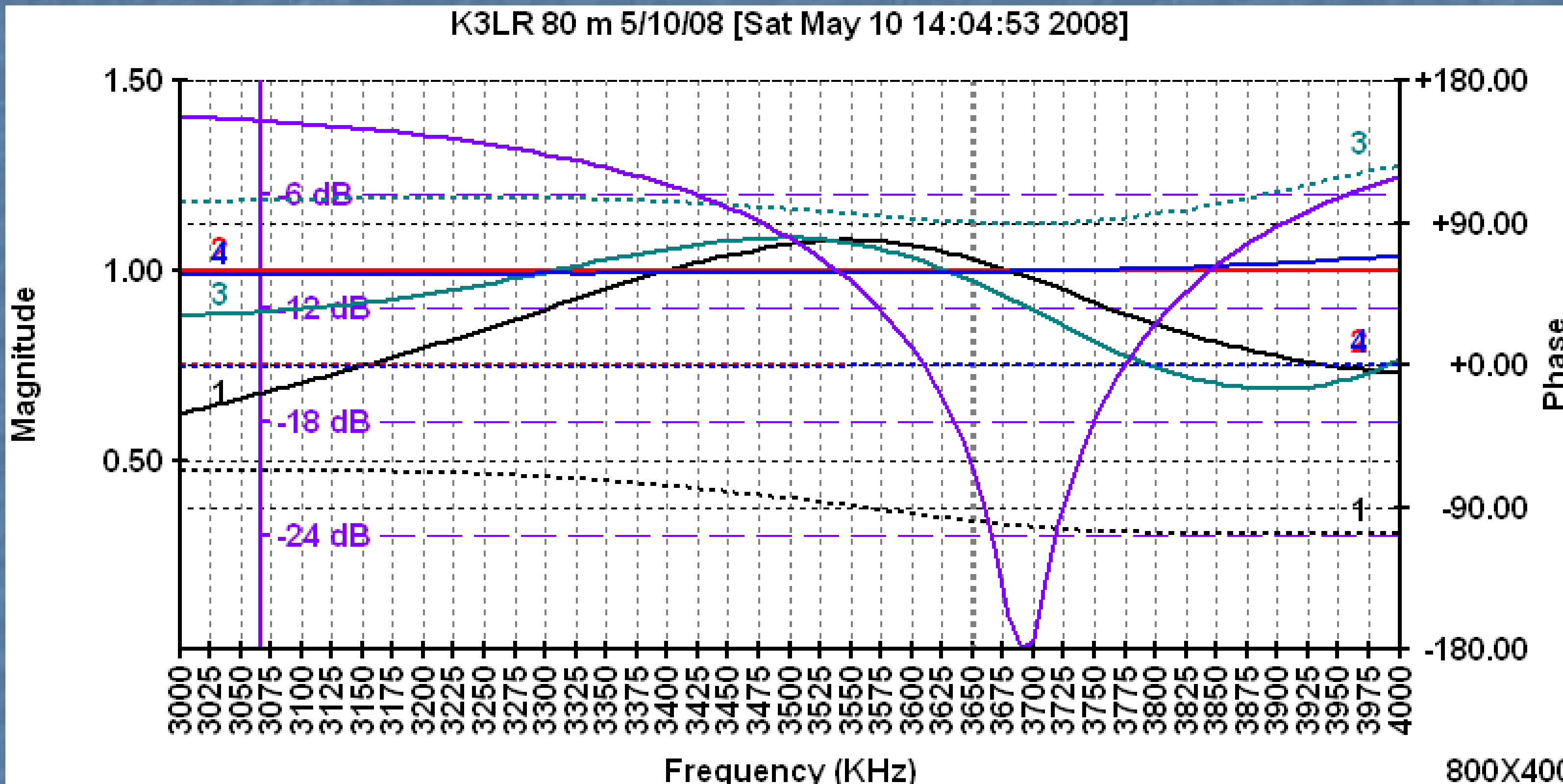


- Crossfire phasing performance.

Applications

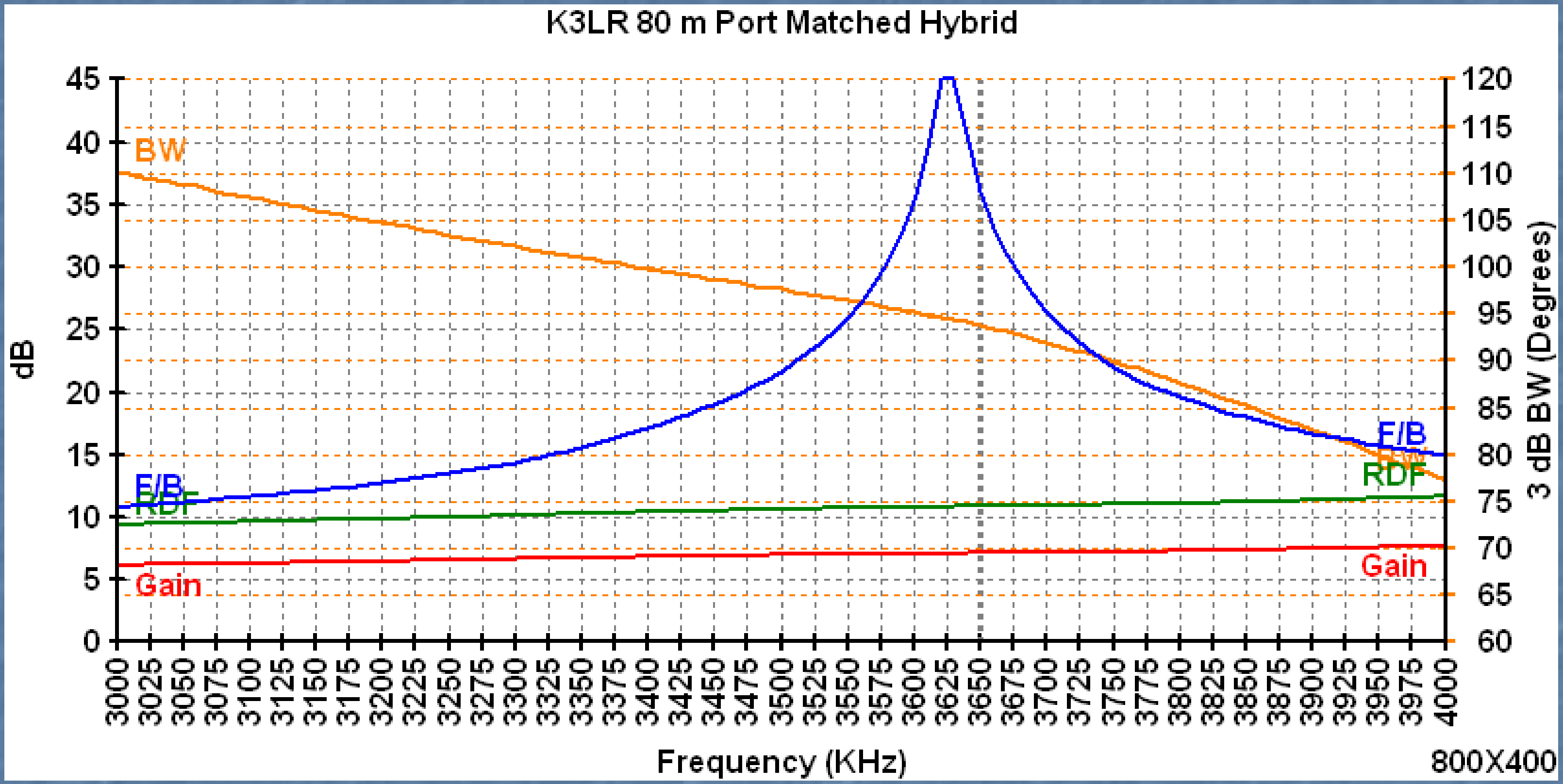
- Port Matched Hybrid Coupler.
  - Insert networks so that the coupler has 50 Ohm loads at the target frequency. Additions were an L network, inductor, and 22° of 50 Ohm transmission line.
  - The coupler will produce a 90 degree shift only when the reflection coefficients on the two ports are the same.
  - Use a lower Fo on the coupler to provide voltage magnitude compensation (around 3.2 MHz).
  - Improve the 180 degree phase inversion transformer.

Applications



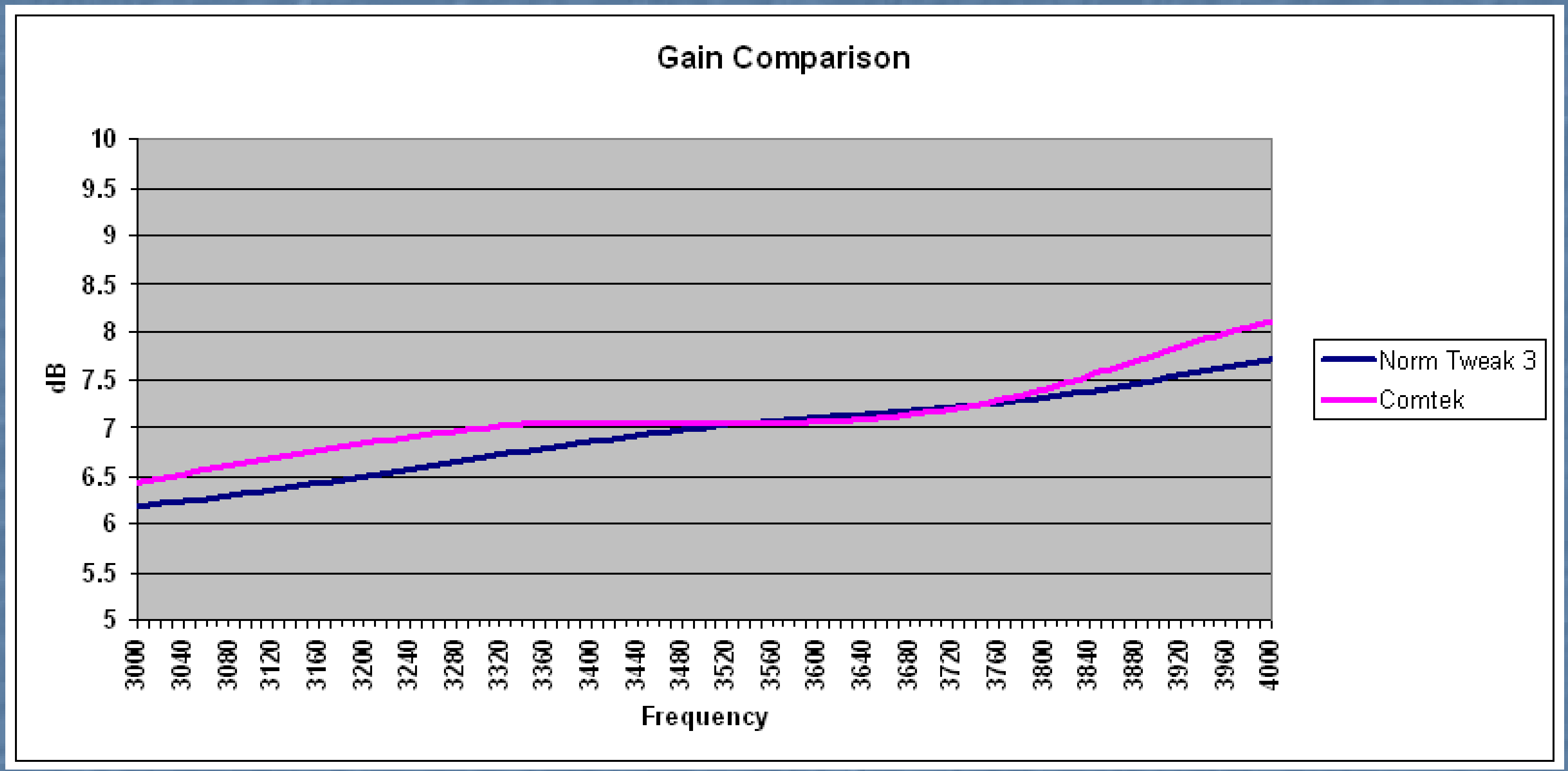
- Relatively flat magnitude and phase response.

Applications



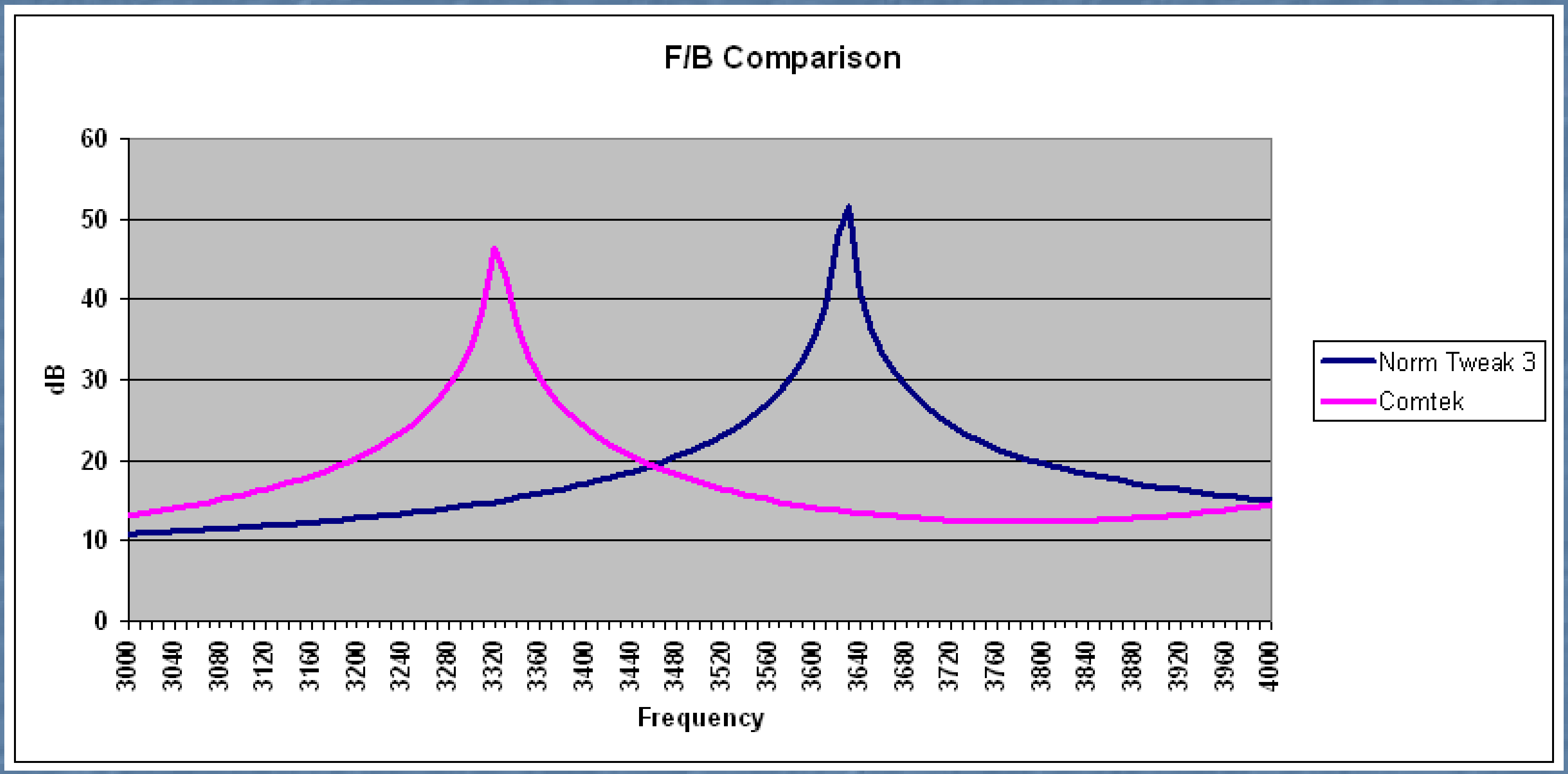
- 300 KHz of at least 20 dB F/B.
- Data can be saved in the .csv file format for continued analysis in Excel.

Applications



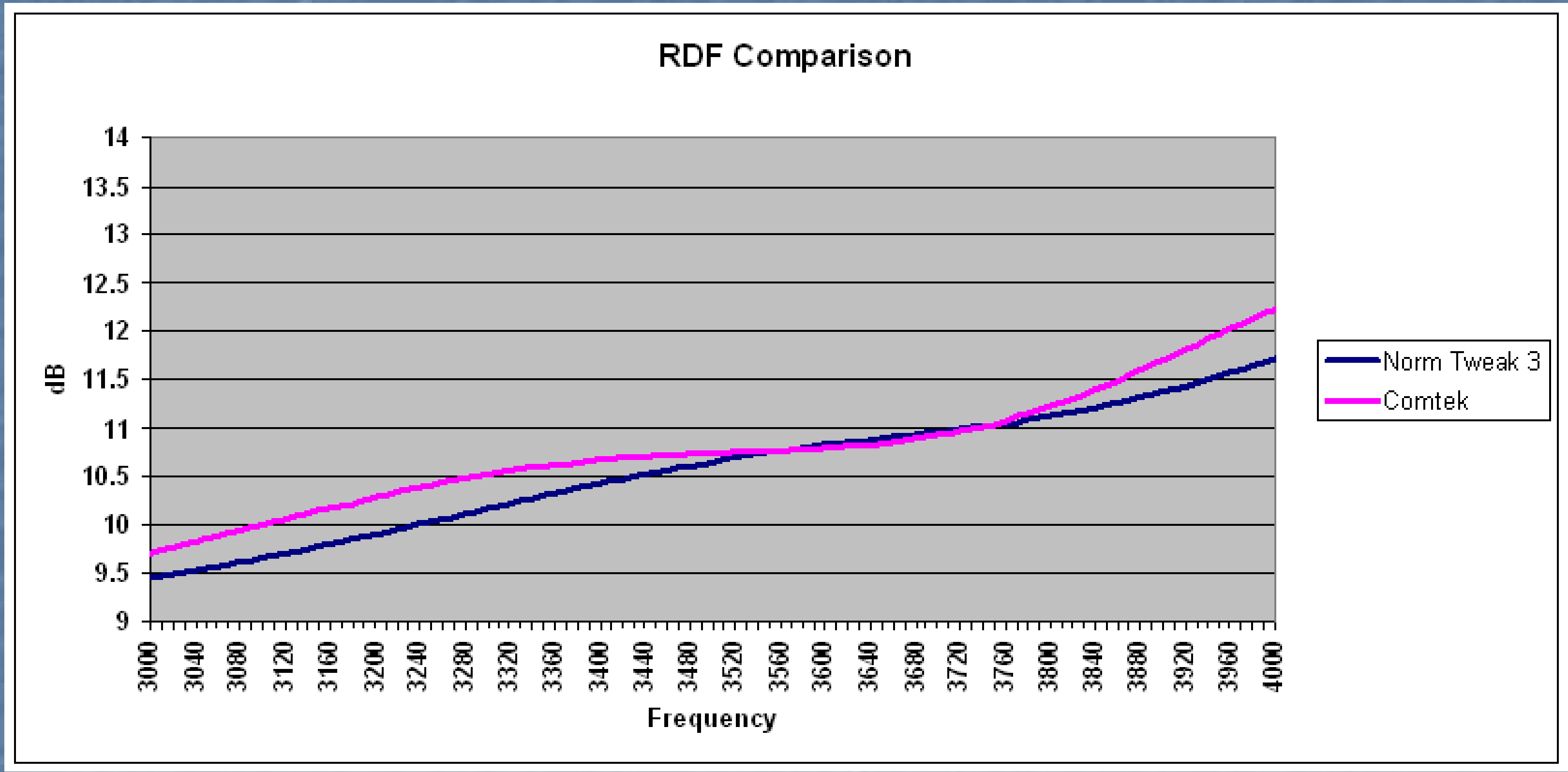
- Comparison between unmodified Comtek and Port Matched Hybrid.

Applications

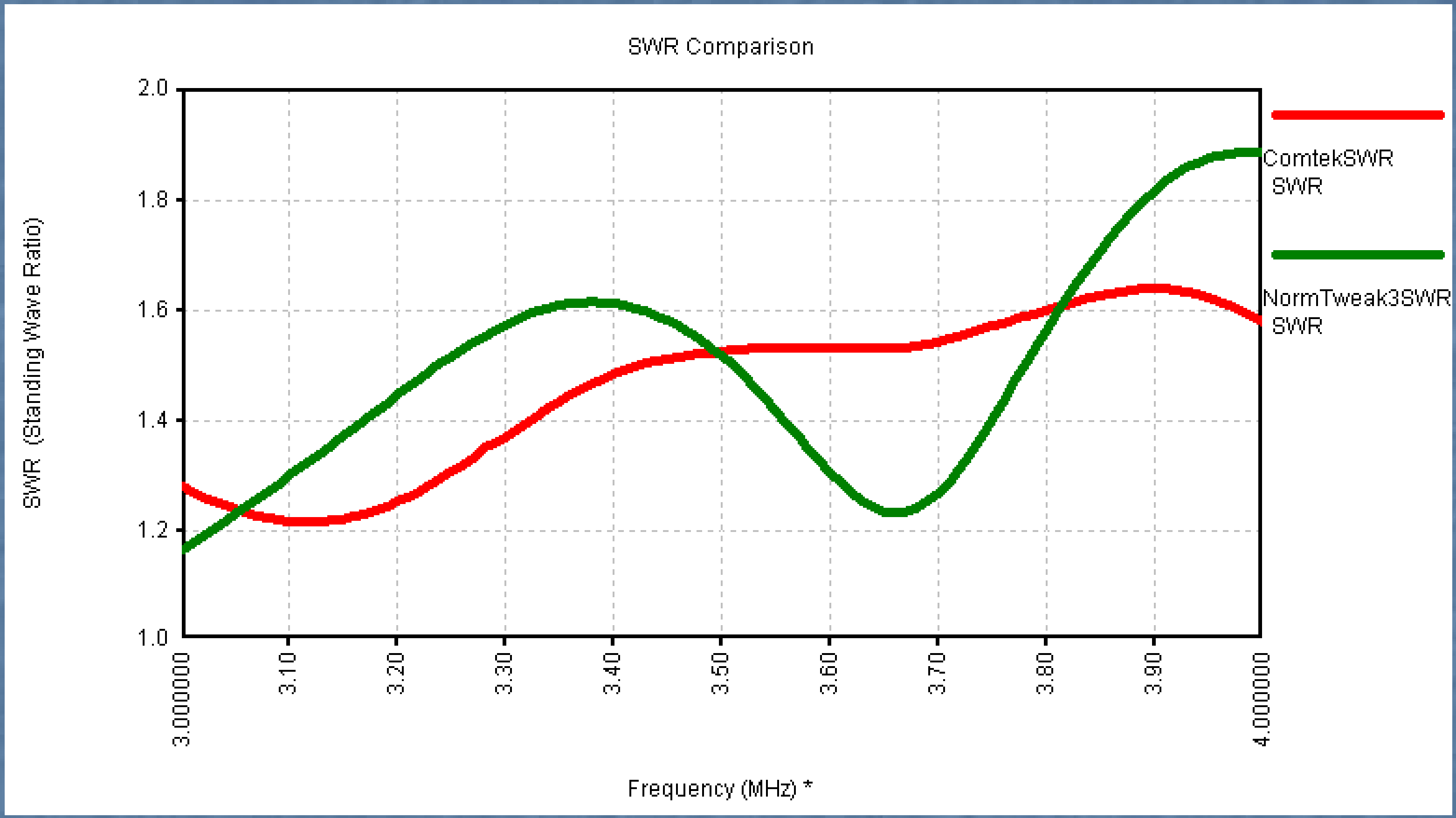


- This is the big difference, moving the F/B peak up into the band.

Applications

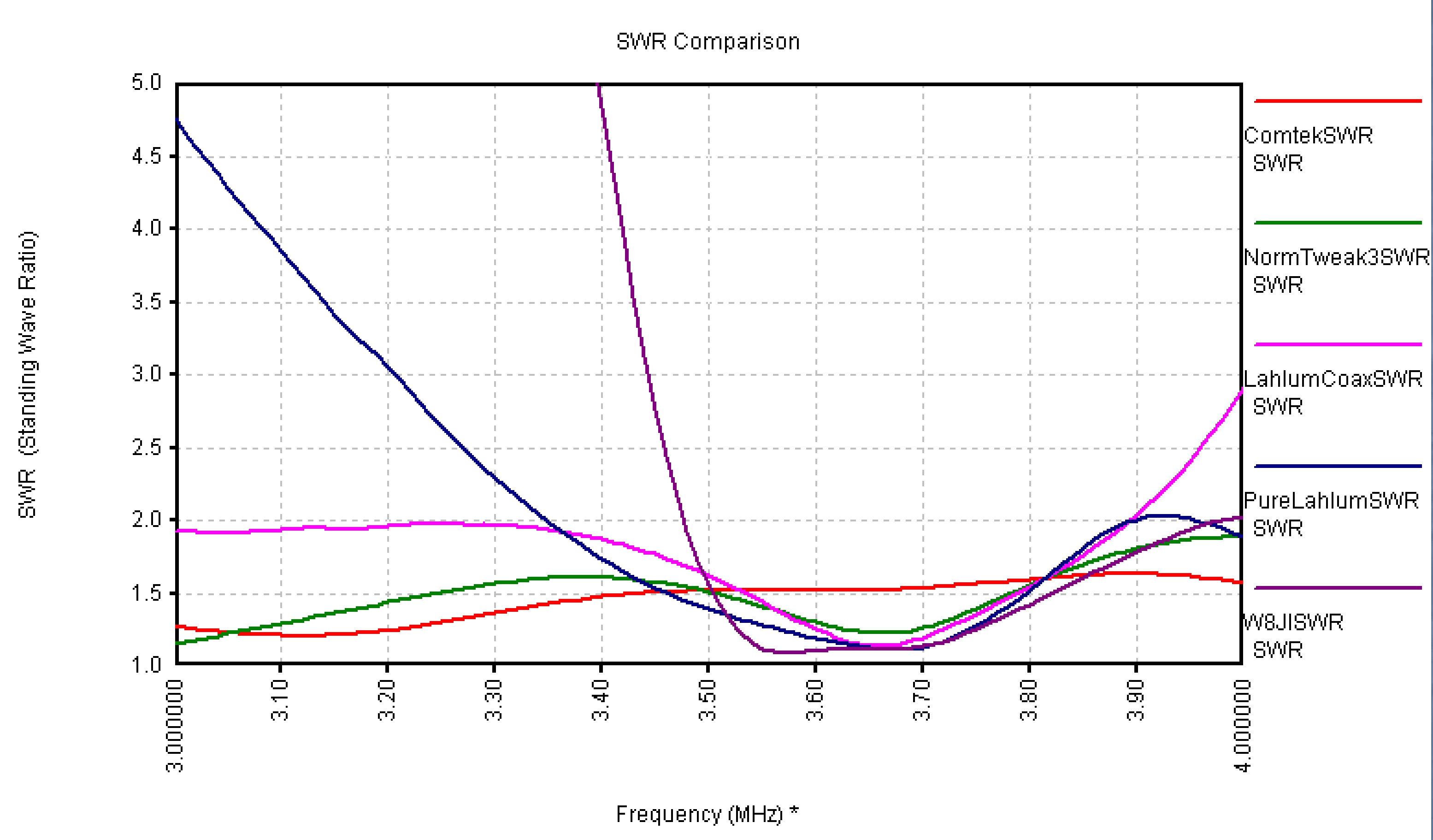


Applications



- How could we forget SWR? SWR measured with VNA.

Applications



- All of the networks have an SWR under 2 within the range of 3500 to 3800 KHz.

5. Summary

- rvm provides accuracy with ease of use.
- Especially helpful for analyzing an entire band.
- Current probes and cables are within the reference (calibration) plane.
- Current probe cables should be heavily choked at both ends.
- A hardware multiplexer is desirable for real time adjustment, but otherwise not necessary.
- rvm (or the approach) can be adapted to other VNAs.