SWEPT FREQUENCY TECHNIQUES FOR EVALUATING AM ANTENNA SYSTEM BANDWIDTH

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Introduction

To assure high quality transmission for stations operating in the AM radio band, the bandwidth characteristics of their transmitting antenna systems must be maintained to high standards. Impedance bandwidth – as presented to a transmitter's final amplifier – is the primary factor that is studied today, and it can be evaluated with measurements made using traditional impedance bridging techniques. The signals radiated from antennas can be subject to other bandwidth-related factors – such as the delay characteristics of the matching equipment and filters, if any, and the pattern bandwidth characteristics of directional antenna systems. Evaluation of these other factors requires measurement of more than just impedance.

The advent of digital transmission within the AM band promises to focus a much higher level of attention on antenna-related bandwidth matters. Not only is it necessary to pay close attention to the symmetry of the load impedance at the final amplifier of the transmitter to minimize unintended phase modulation that can cause a conventional AM signal to interfere with its own digital counterpart, the delay and response characteristics of the networks that lie between the transmitter and the antenna element(s) can have a significant impact on the integrity of the over-the-air digital signal. Additionally, the pattern bandwidth characteristics of a directional antenna system can determine how much of a station's analog coverage area will be able to receive a decodable digital signal.

Although a modern device – the vector network analyzer – is capable of rapidly measuring every characteristic necessary to evaluate the important aspects of RF system bandwidth performance, it has not found widespread use in the AM band. Because vector network analyzers use signals at or near the milliwatt level for their measurements, they are subject to massive interference – and even damage – when connected directly to AM antennas because of the high levels of interference, from other signals and static discharges, that are induced on their towers.

A system has been developed that utilizes a vector network analyzer along with an external amplifier for swept-frequency measurements of AM antennas and their associated RF circuitry under power – with several volts of signal at the test terminals and a high degree of isolation between the antenna and the sensitive test equipment. The system can be used to make conventional impedance sweep measurements much more rapidly than is possible with traditional bridging equipment, and can also make sweep measurements of internal operating impedances, network response characteristics, network phase characteristics, network delay characteristics, and directional antenna element phase and ratio characteristics very efficiently.

About Network Analyzers

Present-day network analyzer technology evolved from the sweep measurement techniques that were used to plot the VSWR-vs-frequency characteristics of antennas at VHF frequencies and above 20 or more years ago. Scalar network analyzers – so named because they do not view the quantities that they measure as complex numbers – made such measurements more convenient when they became available by combining the sweep generator and tracking oscilloscope functions in one box. With the advent of vector network analyzer technology, it became possible to view the complex impedances of antennas instead of just their VSWR characteristics.

A vector network analyzer consists – in a very basic sense – of a sweep generator, three synchronized receivers that detect the relative magnitudes and phases of the signals that are fed into them, and a computer that can process the outputs of two or more of the receivers as appropriate for the type of measurement that is desired. Impedance is just one thing that vector network analyzers can measure – they can be used to measure many other parameters that are described by the relative magnitudes and phases of voltages or currents within a system, such as the response and phase characteristics of the currents entering and leaving a network. Some vector network analyzers have the ability to perform the necessary mathematical transform to convert impedance sweep information at the input of a transmission line into a reflection-vs-distance (time domain) plot, making it possible to use one in place of a traditional time domain reflectometer ("TDR") for finding line faults.

Vector network analyzers fall into two general categories, those which simply have the sweep generator output and three receiver inputs on their front panels for connecting to the external components that are necessary for the desired measurements (with four jacks) and those which have everything necessary for specific measurements inside (with two jacks). Vector network analyzers with four jacks generally use external test sets that are designed for them. Such test sets fall into two categories – S-parameter test sets that are capable of measuring the characteristics of a device under test ("DUT") bi-directionally and transmission/reflection test sets that measure the input and pass characteristics of a DUT with the signal flow in one direction. Vector network analyzers with two jacks are very convenient for typical laboratory applications, but they lack the flexibility to be used with custom external devices for unusual applications – such as high power measurements on AM directional arrays.

The High-Power Measurement System

The system that has been developed for AM band measurements at high power is based on a four-jack vector network analyzer. Both a Hewlett-Packard model 8753C analyzer and an Agilent Technologies model 4395A analyzer have been employed successfully in the system, the latter having the advantage of a built-in 3.5-inch magnetic disk drive to store its screen images – making it unnecessary to have a printer or plotter attached during its use.

In place of a transmission/reflection test set, the system uses a linear power amplifier, followed by a 12 dB power attenuator, and then a broadband, high-power directional coupler that was custom designed for optimum performance within the range of 0.5 to 2.0 MHz. The power amplifier boosts the low-level RF output of the analyzer to a much higher voltage for application to the DUT. The voltage is dropped by the attenuator before entering the directional coupler – both for amplifier load isolation and to attenuate interference signals coming from the DUT, which are reflected at the amplifier, by at least 24 dB before they appear at the forward port of the directional coupler. The reference receiver, which phase-locks the analyzer, is therefore isolated by any interference that is present on the DUT by at least 24 dB. The 12 dB attenuator that follows the amplifier should be rated for higher power than the amplifier, for continuous operation, and should also be rated for bi-directional power flow if it is to be used to measure antennas that are near other AM radio stations that induce significant voltages on them.

The directional coupler can be used by itself – with its reflected port connected to the analyzer's receiver A – for impedance measurements of a DUT. It can also be used to derive the reference signal necessary to phase-lock the analyzer with the reference receiver connected to its forward port and receivers A and B connected in other configurations.

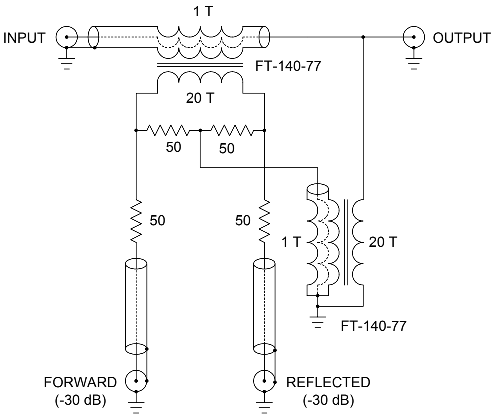


Figure 1 – Directional Coupler

Figure 1 shows the circuit of the directional coupler that was developed for this system. Constructed in a 3.5 X 4.5 X 2 inch metal box with minimal lead length between the two transformers to minimize strays, it provides more than 40 dB directivity over the frequency range of the AM band and was designed to withstand more than 100 volts across the DUT. The transformers are wound on Amadon Associates ferrite toroids. If a directional coupler for use between 3 – 30 MHz is desired, FT-114A-61 ferrite toroids may be substituted for those shown. The circuit requires precision, non-inductive 50 ohm resistors for accurate measurements. Caddock MP-820 power film resistors, which have a resistance tolerance of one percent and are rated for 2.25 watts when free-mounted, are employed in the directional coupler circuit.

An ENI type 240L linear amplifier is employed by the system. It has 50 dB of gain and is rated for a continuous power output of 40 watts over the frequency range of 20 KHz to 10 MHz, which is achieved with the analyzer's power output set to –4 dBm. Other amplifiers should work well in the system, although their power must be sufficient to overcome the level of interference that is encountered when the system is connected to an antenna.

Impedance Measurements

A network analyzer measures impedance by processing reflection coefficient information from a directional coupler with the signal from its internal sweep generator passing through it into the DUT. Since that process becomes more prone to error as the measured impedance departs further from the characteristic impedance of the directional coupler – typically 50 ohms – a different approach is used by modern impedance analyzers which are capable of very precise measurement from a fraction of an ohm to several megohms. It has been found, however, that – with high quality directional couplers – network analyzers can measure impedance values within the rated accuracy of the bridges that have traditionally been used for impedance measurements at AM frequencies up to a VSWR of greater than 10:1 referenced to the characteristic impedance. Most impedances that are encountered within AM antenna systems fall within that range.

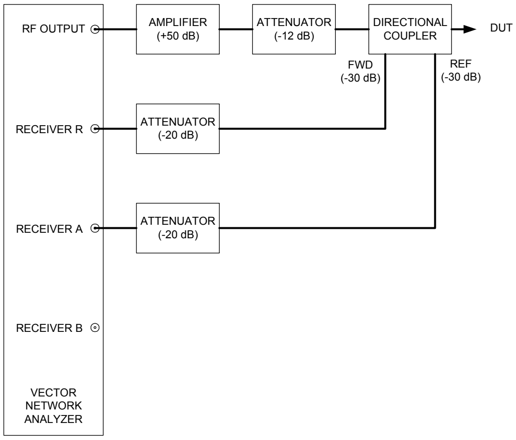


Figure 2 – Impedance Measurement System

Figure 2 shows a block diagram of the system configuration that may be used for impedance measurements at the input of a DUT – such as at a directional antenna common point or at the termination of the final amplifier of a transmitter. For an RF output of –4 dBm from the analyzer, the attenuators limit the signal level after amplification to –12 dBm at the receiver inputs – a level that is well within the range of the analyzer.

The IF bandwidth that is selected for the analyzer determines both the resolution with which measurements are made and the length of time required for each successive frequency sweep. For impedance measurements (and most of the other measurements that are made on AM antenna equipment), an IF bandwidth setting of 300 Hz has been found to be more than satisfactory.

Vector network analyzers employ very sophisticated mathematical processing to achieve a high degree of accuracy – including compensation for the effects of the coaxial cable used to connect the system to the DUT – after they are calibrated with known open circuit, short circuit, and characteristic impedance standards. They are capable of covering a much wider frequency range than the AM band – typically from a few hundred KHz to several GHz – and precision calibration kits are normally recommended for use with them. Such calibration kits have been found to be unnecessary for making accurate measurements over the relatively narrow frequency range of the AM band, as long as a precision 50 ohm non-inductive resistor is used for the "terminated" calibration, a low-inductance short circuit is used for the "short" calibration, and a low stray-capacitance open circuit is used for the "open" calibration. These conditions are not nearly as hard to meet at 1.0 MHz as they are at 1 GHz, or even 100 MHz – so it has been found to be sufficient to open and short test clips attached to the end of the coaxial cable that is used to connect the directional coupler to the DUT and then attach them to a low-inductance precision resistor, as prompted by the analyzer during the calibration process.

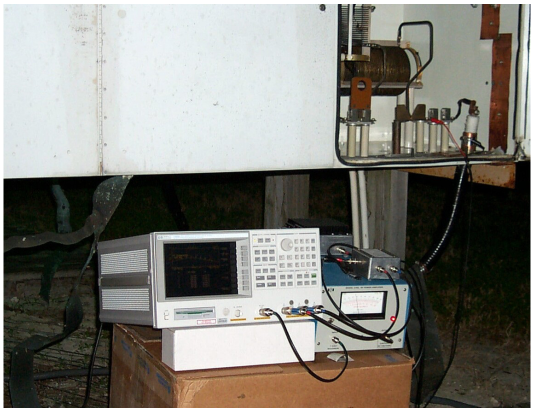
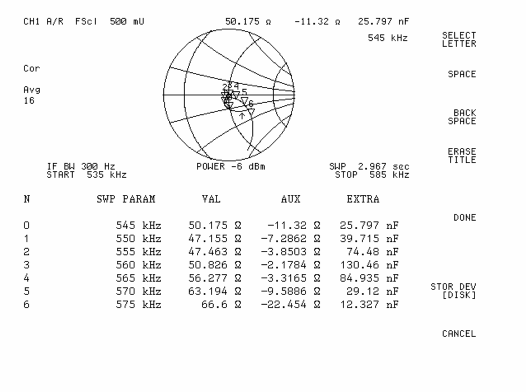


Figure 3 – Impedance Measurements at ATU Input

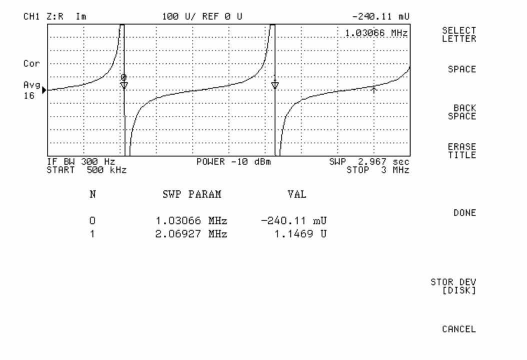
Figure 3 is a photograph of the system being used to measure the input impedance of a nondirectional antenna's tuning unit. Figure 4 shows both the Smith Chart plot and the tabulation of the impedance sweep that were generated by the analyzer.



```
CH1 A/R  FScl  500 mU                50.175 Ω   -11.32 Ω   25.797 nF
                                                             545 kHz
Cor

Avg
16

    IF BW 300 Hz                POWER -6 dBm              SWP  2.967 sec
    START  535 kHz                                         STOP  585 kHz

N          SWP PARAM       VAL          AUX         EXTRA

0            545 kHz     50.175 Ω     -11.32 Ω    25.797 nF
1            550 kHz     47.155 Ω    -7.2862 Ω    39.715 nF
2            555 kHz     47.463 Ω    -3.8503 Ω     74.48 nF
3            560 kHz     50.826 Ω    -2.1784 Ω    130.46 nF
4            565 kHz     56.277 Ω    -3.3165 Ω    84.935 nF
5            570 kHz     63.194 Ω    -9.5886 Ω     29.12 nF
6            575 kHz       66.6 Ω    -22.454 Ω    12.327 nF
```

Figure 4 – Impedance Measurement Results

The ability to measure impedances over a wide frequency range rapidly makes the system useful for other things – such as evaluating transmission lines. Even if the analyzer does not have the option that allows it to function as a TDR, a sweep of measurements such as is shown on Figure 5 can be interpreted to find the length of a transmission line that is open-circuited or short-circuited on its far end by noting the frequency spacing between successive resonant points – the line being one-half wavelength, or 180 elecrtical degrees in length, at that frequency. Despite the fact that the process of measuring impedances near zero (at the resonant points) is imperfect due to the nature of the reflection coefficient method used by vector network analyzers, it has been found that line lengths may be determined with sufficient accuracy for practical directional antenna work by this method.



```
CH1 Z:R   Im              100 U/ REF 0 U                 -240.11 mU
                                                          1.03066 MHz
Cor

Avg
16
    IF BW 300 Hz             POWER -10 dBm               SWP  2.967 sec
    START  500 kHz                                        STOP  3 MHz

          N          SWP PARAM        VAL

          0        1.03066 MHz    -240.11 mU
          1        2.06927 MHz      1.1469 U
```

Figure 5 – Transmission Line Measurements

The system is also useful for the initial setup of RF matching and phase shifting networks, since the ability to connect a coaxial cable of any practical length to the directional coupler and then calibrate it for accurate impedance measurement at its far end makes it possible to measure and adjust network branches without having to place the measurement equipment nearby. With traditional bridging methods, it is necessary to constantly move the equipment when setting up the networks within a phasor cabinet, for instance. With the vector network analyzer system, the equipment can be placed within view of a phasor cabinet and not moved. A test cable of sufficient length to reach all of the networks can be calibrated once and then used repeatedly during the setup process.

Operating Impedance Measurements

Figure 6 shows how the system may be configured to use two directional couplers to sweep the operating impedances of a directional antenna system where the transmission lines exit its phasor cabinet. Such measurements can be very meaningful for troubleshooting both impedance bandwidth and pattern bandwidth problems in arrays.

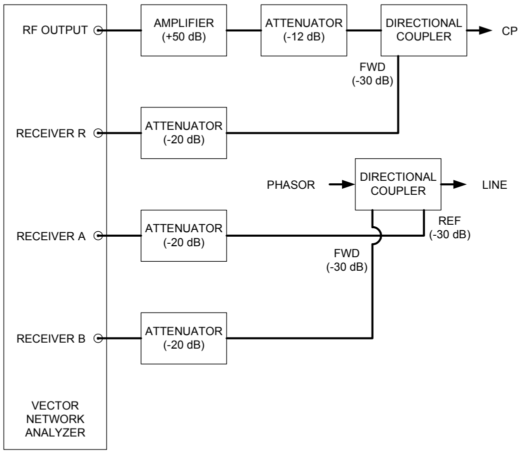


Figure 6 – Operating Impedance System

The directional coupler that is used to measure the operating impedance supplies its forward and reverse samples to the B and A receiver inputs of the analyzer, respectively. Short leads must be used at its input and output to minimize its insertion effects on the antenna parameters. The analyzer is configured to use the two receivers for measurement, and the input to the reference receiver – which is derived from the forward port of the directional coupler at the common point – is only used to phase-lock the system. This allows the system to operate with a high degree of interference immunity – even when measuring the line matches of the low-power towers of an array – owing to the isolation of the reference receiver input from other signals that are picked up by the antenna.

Measuring Network Response Characteristics

Figure 7 shows the system configured to use the A and B receiver inputs to measure the response of a network using current transformers at its input and output. The measurements may be made with the network driven by the output of the directional coupler and terminated in a load, as shown, or with the network connected for normal operation with the antenna input driven by the output of the directional coupler.

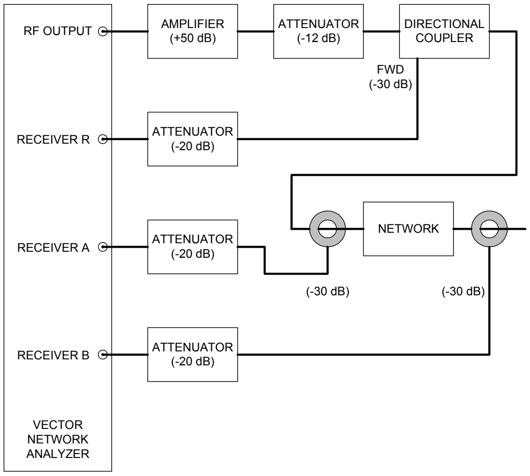


Figure 7 – Response Measurement System

The details of the current transformer design are shown on Figure 8. The secondary consists of 32 turns of RG-174 miniature coaxial cable wound onto the ferrite toroid and connected as shown. The test setup to measure the response of an antenna matching/diplexer unit, with a current transformer at one station's input and another at the combined output, is shown in Figure 9. Figure 10 is a close-up photograph showing the transformer at the unit's input.

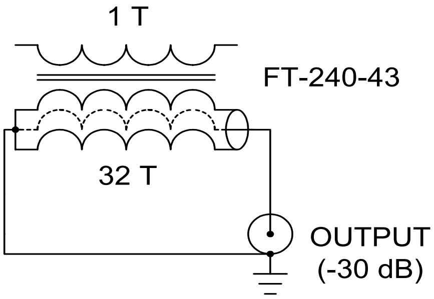


Figure 8 – Current Transformer

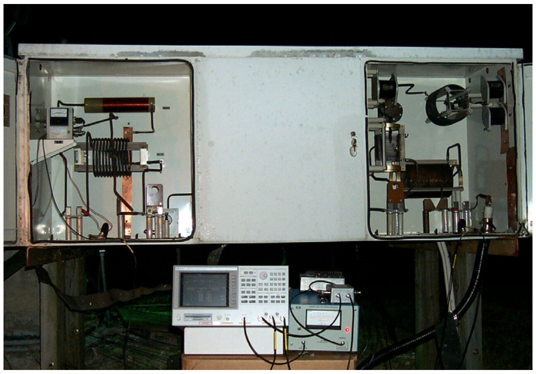


Figure 9 – Response Measurements

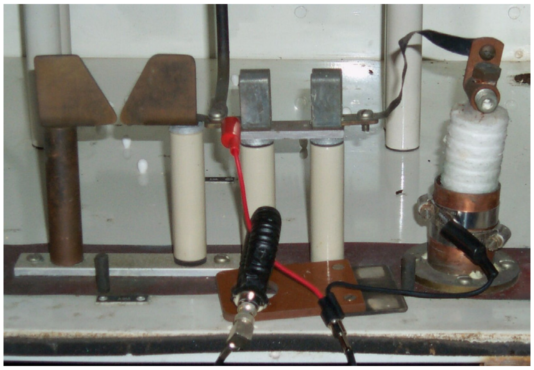
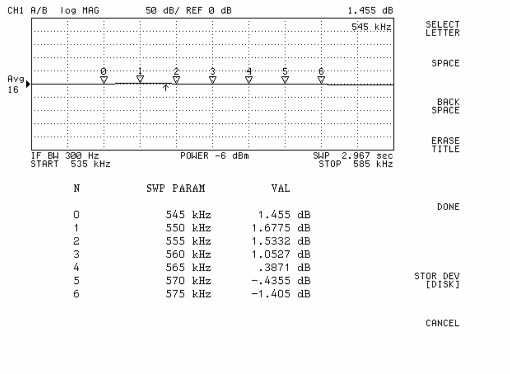


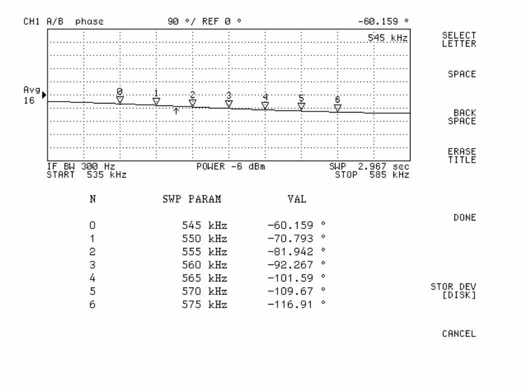
Figure 10 – Current Transformer at ATU Input

Figure 11 shows the measured response in dB and Figure 12 shows the measured phase shift. Figure 13 shows the measured delay characteristics. In addition to phase shift and delay characteristics, vector network analyzers can also produce a screen showing a plot of the departure from linear phase – a related quantity that may be convenient to use when analyzing the transparency of a network or system of networks.



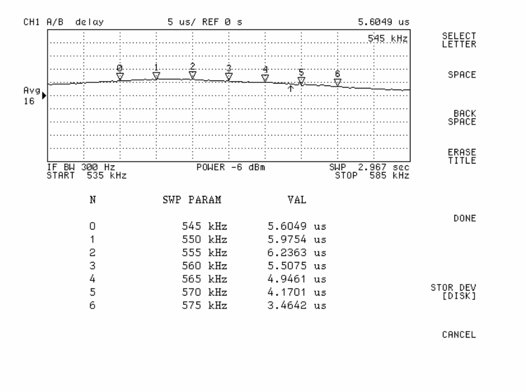
```
CH1 A/B  log MAG        50 dB/ REF 0 dB          1.455 dB
                                                  545 kHz
IF BW 300 Hz             POWER -6 dBm         SWP  2.967 sec
START  535 kHz                                STOP  585 kHz

        N          SWP PARAM         VAL

        0            545 kHz       1.455 dB
        1            550 kHz      1.6775 dB
        2            555 kHz      1.5332 dB
        3            560 kHz      1.0527 dB
        4            565 kHz       .3871 dB
        5            570 kHz     -.4355 dB
        6            575 kHz     -1.405 dB
```

Figure 11 – Measured Response



```
CH1 A/B  phase          90 °/ REF 0 °             -60.159 °
                                                   545 kHz
Avg
16
IF BW 300 Hz           POWER -6 dBm           SWP  2.967 sec
START  535 kHz                                 STOP  585 kHz

     N        SWP PARAM          VAL

     0          545 kHz      -60.159 °
     1          550 kHz      -70.793 °
     2          555 kHz      -81.942 °
     3          560 kHz      -92.267 °
     4          565 kHz      -101.59 °
     5          570 kHz      -109.67 °
     6          575 kHz      -116.91 °
```

Figure 12 – Measured Phase Shift Sweep



```
CH1 A/B  delay           5 us/ REF 0 s             5.6049 us
                                                   545 kHz
Avg
16
IF BW 300 Hz           POWER -6 dBm           SWP  2.967 sec
START  535 kHz                                 STOP  585 kHz

     N        SWP PARAM          VAL

     0          545 kHz      5.6049 us
     1          550 kHz      5.9754 us
     2          555 kHz      6.2363 us
     3          560 kHz      5.5075 us
     4          565 kHz      4.9461 us
     5          570 kHz      4.1701 us
     6          575 kHz      3.4642 us
```

Figure 13 – Measured Delay Sweep

The system may be used in its response measurement configuration to evaluate and adjust filters such as are employed to eliminate intermodulation products from transmitters and for multiplexing more than one frequency on a single antenna. Such work goes very quickly with the system. An analyzer IF Bandwidth setting of 100 Hz has been found to be more than sufficient for filter tuning work, while a setting of 300 Hz can be used for measuring the response of simpler networks.

Measuring Directional Antenna Parameters

Figure 14 shows the configuration that may be used to measure the phase and ratio-vs-frequency characteristics of a directional antenna system's elements. The common point is driven by the directional coupler which derives the signal for the analyzer's reference receiver input. The antenna monitor sampling line of the reference tower is connected to the B receiver's input. The other sampling lines are switched to the A receiver's input and the analyzer is alternately set to measure the magnitude and phase relationships of the A and B inputs for each tower. Figures 15 and 16 show how the ratio and phase of the current flowing in a tower of an array may vary with frequency, respectively.

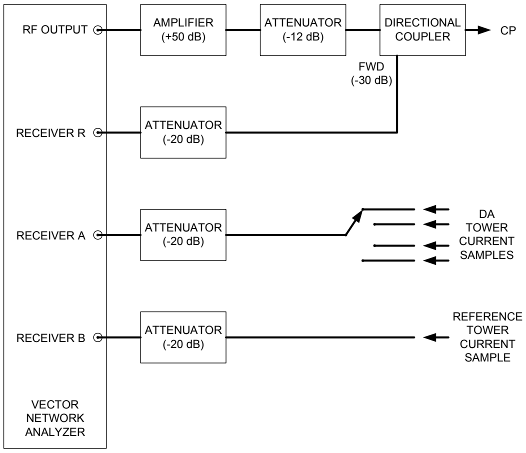
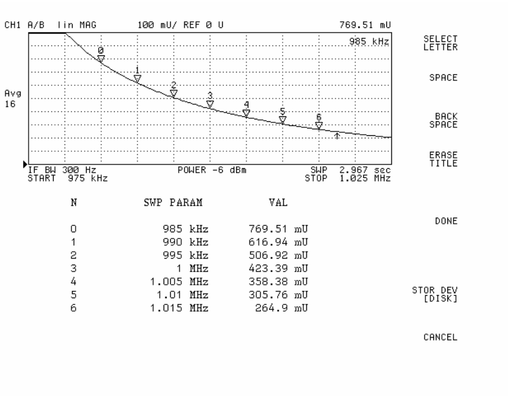
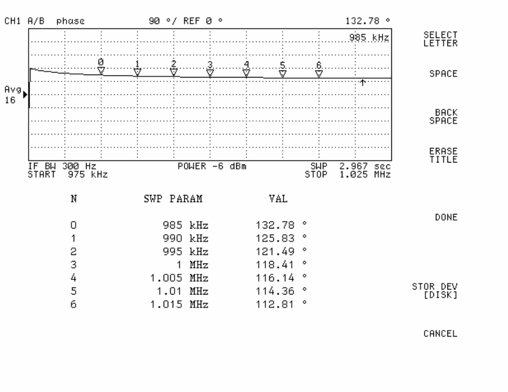


Figure 14 – DA Phase and Ratio Measurements



```
CH1 A/B  lin MAG       100 mU/ REF 0 U            769.51 mU
                                                   985 kHz
Avg
16
IF BW 300 Hz           POWER -6 dBm           SWP  2.967 sec
START  975 kHz                                 STOP  1.025 MHz

     N        SWP PARAM          VAL

     0          985 kHz      769.51 mU
     1          990 kHz      616.94 mU
     2          995 kHz      506.92 mU
     3            1 MHz      423.39 mU
     4        1.005 MHz      358.38 mU
     5         1.01 MHz      305.76 mU
     6        1.015 MHz       264.9 mU
```

Figure 15 – Measured Ratio Sweep



```
CH1 A/B  phase          90 °/ REF 0 °              132.78 °
                                                   985 kHz
Avg
16
IF BW 300 Hz           POWER -6 dBm           SWP  2.967 sec
START  975 kHz                                 STOP  1.025 MHz

     N        SWP PARAM          VAL

     0          985 kHz       132.78 °
     1          990 kHz       125.83 °
     2          995 kHz       121.49 °
     3            1 MHz       118.41 °
     4        1.005 MHz       116.14 °
     5         1.01 MHz       114.36 °
     6        1.015 MHz       112.81 °
```

Figure 16 – Measured Phase Sweep

It may be necessary to use attenuator values that differ from those that are shown at the analyzer's receiver inputs on Figure 14, depending on the sensitivity of the sampling devices that are employed in the antenna monitor sampling system. The voltages at the terminals of the antenna monitor can be compared to the voltage that is known to be present at the common point under normal operation to determine the dB isolation between the directional antenna's input and the sampling lines when they are terminated in 50 ohm loads - and appropriate attenuator values can then be chosen.

Information on how the tower ratios and phases vary with frequency may be used to evaluate pattern bandwidth. The measured antenna element parameters at carrier and sideband frequencies may be used to calculate the changes in far-field magnitude and phase that occur at different azimuths, using computer software such as the Mininec Broadcast Professional package. The far-field response may then be calculated directly from the magnitude excursions. The delay characteristics may be calculated from the phase characteristics at the azimuths of interest.

Further Comments

The capabilities of network analyzers far exceed the specific applications that are described herein, and anyone wishing to use the system will do well to become thoroughly familiar with them by studying their instruction manuals and any other educational materials that are available. The information provided herein is for general use only and assumes that any user will be competent in the use of vector network analyzers before the described procedures are undertaken.

Although the system has been successfully used under a variety of conditions at different transmitter sites, the experience with it is not exhaustive and there may be some cases where its usefulness is limited by interference or other factors that are yet unknown. While the system has proven very effective for evaluating antenna performance and setting up networks where frequency sweep information is useful, the battery-powered convenience of current model bridging equipment still recommends it for simple single-frequency impedance measurements – particularly in equipment that is located outdoors. For that convenience, and the ability to measure very high and very low impedances that are outside the accurate range of the vector network analyzer system – RF bridges and generator/receiver units will continue to be standard equipment for engineers who service and adjust AM antennas.

Conclusion

With the high power measurement system described herein, vector network analyzers may be utilized for both conventional impedance measurements and the specialized tests that are required to evaluate the transparency of AM antenna systems for digital signal transmission. Because automatic swept-frequency techniques are used, the bandwidth characteristics of an antenna system can be evaluated with minimal station down time.

As of yet, no antenna system performance requirements have been issued by the developer of the digital transmission system that has been approved for use by AM stations in the United States. Presumably, the requirements will be forthcoming and engineers will then be able to use the vector network analyzer system to obtain the information necessary to predict the performance of antenna systems under "as built" conditions and, where necessary, devise corrective measures.

References:

1) "Using a Network Analyzer to Characterize High-Power Components," Agilent Technologies Application Note 1287-6

2) "Exploring the Architectures of Network Analyzers," Agilent Technologies Application Note 1287-2

3) "Understanding the Fundamental Principles of Vector Network Analysis," Agilent Technologies Application Note 1287-1

4) "Applying Error Correction to Network Analyzer Measurements," Agilent Technologies Application Note 1287-3

5) "Advanced Impedance Measurement Capability of the RF I-V Method Compared to the Network Analysis Method," Agilent Technologies Application Note 1369-2