ADVANCED RF SYSTEM MEASUREMENT TECHNIQUES

James T. Stenberg and Walter Pries
Micro Communications, Inc.
Manchester, New Hampshire

ABSTRACT

Modern vector network analyzers with time domain capability provide the user with error-corrected, computer controlled RF system measurements and hard copy results. The use of error-correction yields accuracy never before obtainable. Microprocessor control makes measurement of complex impedance, insertion loss, and group delay, quick and simple.

This paper discusses these advanced measurement techniques and demonstrates tests on dual channel combiners, long transmission runs, and ACTV diplexers. It will familiarize broadcasters with how these tests can improve the efficiency and on air quality of their TV or FM plant, as well as evaluate RF system performance for ACTV/HDTV signals.

INTRODUCTION

Broadcast engineers have long known that low loss, low reflection RF systems maximize plant efficiency and quality. The reasons are obvious; lower loss means lower electricity bills for the same ERP. Low reflections (VSWR) means clearer video as well as increased efficiency. Low VSWR at the tube output assures optimum power transfer to the system. Removing antenna and transmission line reflections wards off the threat of "ghosts". Unfortunately, old loss and VSWR measurement equipment was often bulky, unstable, and produced inaccurate results. Higher electricity costs and increased transmitter efficiencies have pushed RF system performance requirements beyond the limits of this old equipment. New measurement techniques and equipment provide a quantum leap in the resolution and accuracy obtainable. A recently introduced network analyzer, the Hewlett Packard 8753A, utilizes these techniques. Both the RF system manufacturer and the engineer in the field benefit from it's use.

NETWORK ANALYZER BACKGROUND

To begin our discussion of these techniques we should start with a short explanation of the theory behind the network analyzer. A network analyzer determines the transmission and reflection characteristics (impedance and insertion loss) of any device connected between it's two ports. It does this by relating the devices input and output signals to a known reference signal. Once the device's magnitude and phase responses (vectors) have been obtained its complex impedance, insertion loss, and group delay can be determined. By finding the complex s-parameter vectors of any two-port network, it's performance can be completely defined.

The difference between vector and older scalar analyzers is that a vector analyzer measures the systems complex response rather than its magnitude only response. It is this vector capabilty which permits mathematical manipulation of the results and removal of measurement uncertainty. Error vectors that can be mathematically subtracted from the obtained response are found during a calibration routine. Error correction has made it possible to remove the impedance and loss characteristics of the test adapters from the device measurement. Now, by placing known values of impedance at the ends of the test cables the analyzer can reposition its reference ports to their ends. Figure 1 shows the effects of correction on the measurement of a band pass filter's VSWR using high grade lab cables. The figure shows that the uncorrected values are quite different and higher than those with the cable errors removed.

Modern vector network analyzers consist of four basic units (figure 2) combined into one frame. This produces a self-contained measurement system that is easily transported. The most important of the units is a synthesized sweeper source. A synthesizer is used rather than an old fashioned sweeper due to its inherent stability and frequency resolution. Its discrete measurement point capability

(selectable from 201 to 1601) makes mathematical manipulation simple. Stopping at each frequency point, obtaining a response vector, storing, and displaying the data is all done almost instantaneously. The second of the analyzer units is the signal separator. A signal from the source is applied to the device under test and the separator extracts a sample of the forward signal as a reference. The reflected and transmitted signals of the device are also sampled by the separator.

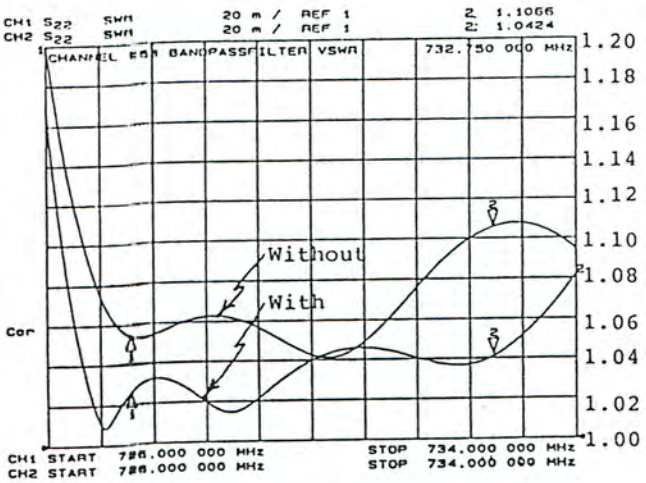

FIGURE 1
FILTER VSWR WITH AND
WITHOUT ERROR CORRECTION

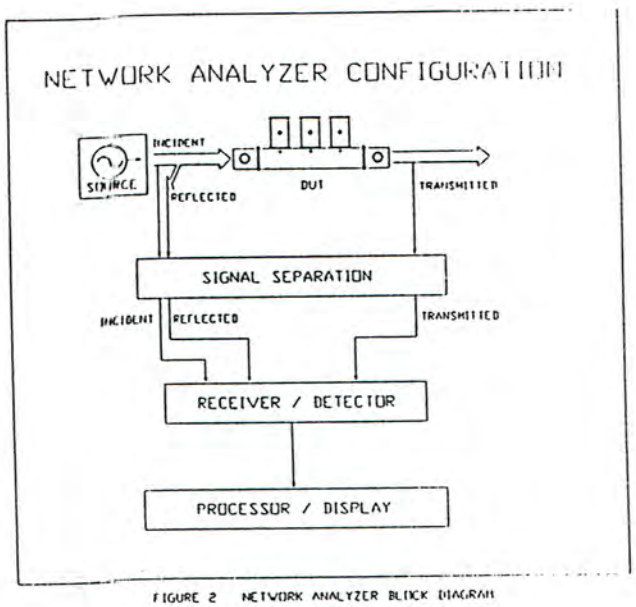

FIGURE 2 NETWORK ANALYZER BLOCK DIAGRAM

These signals; incident, reflected, and transmitted are then applied to the inputs of three phase-locked receivers. These convert the signals to an IF frequency and digitize them. The signals now in digital form go into the processor/display unit. Here they are modified for presentation on the CRT. The processor contains storage space for all of the data from each sweep of the device, any necessary math logic, as well as five instrument set-ups. A main micro-processor drives and coordinates all functions of the analyzer. The data can be stored in memory and displayed in various formats; linear, logarithmic, phase, group delay, smith chart, and polar. Changes in format are made without retaking the measurement. All measurement and display parameters are easily adjusted from the front panel.

The analyzer contains an IEEE-488 computer bus which allows remote operation of the analyzer. Completely automated testing can be done by joining a computer to the bus. The bus also drives a multi-pen plotter for hard-copy output. A built in graphics program directs the plotter to produce exact multi-color duplicates of the screen. This method differs from old x-y plotters by producing a fully labeled and graphed plot from a blank page. Special graph paper is not necessary.

PRECISION MANUFACTURING TOOL

The analyzer is used extensively for the tuning of RF systems and components in the factory. Large systems are assembled from a multitude of components, each separately checked with the analyzer. Some components require tuning to insure that the entire system VSWR is low. The accuracy of the analyzer is extremely important at this point since errors accumulate when combined in a system. To demonstrate, take four components and match them for unity VSWR with both old and new measurement systems. Then assemble the components as a system and compare the results. Both measurement systems have values of VSWR uncertainty which affect the displayed results. Uncertainty is a measure of the overall analyzer directivity. Poor directivity means more uncertainty. The Contributors to bad directivity consist of; limited coupler directivity, poor source match, varying test set frequency response, and high VSWR test cables. The new analyzer, however, has a calibration routine to remove these constant uncertainty terms. The old one can not remove their effects. Typical total directivity for the old system assuming type "N" couplers, adapters, and cables would be -34dB or a VSWR uncertainty of 1.041. For the new analyzer after correction, -44dB and 1.013 are typical values. If each component is perfectly matched on the respective systems we find that the old system yields

actual VSWR values between 1.00 and 1.04. Those tuned with the new system range between 1.00 and 1.01. When the four components are assembled and measured as a system the accumulation of these uncertainties can be dramatic. An input VSWR of 1.174 may actually be present with the old system and 1.053 with the new analyzer. These numbers assume that all the mismatches are at the correct phase to sum together. Actual system values may or may not be lower. The more components assembled into a system the worse the problem becomes.

The first step in any component or system tuning is to obtain matched test transitions. For coax systems these transitions adapt the line size down to type "N". Coax transitions are matched using two identical adapters on the ends of a 20 foot length of line. Each adapter is adjusted for minimum VSWR looking from the other end. The minimization is repeated until unity VSWR is obtained at both ends. The analyzers data memory is used to store the results of one ends measurement. While adjusting the other end the memory data obtained is displayed and a direct comparison between the ends is made. This technique results in two transitions, tuned simultaneously with very little effort. Waveguide system testing utilizes waveguide to type "N" adapters. The adapter is tuned by bolting it to the end of a straight waveguide section containing a low VSWR waveguide sliding load. Match is obtained by making a tight impedance grouping which moves around the smith chart center as the load is moved.

VSWR optimization of most coaxial system components is unnecessary. If tuning is needed, it is done by placing correctly sized and located capacitive rings on the inner conductor. The rings are placed as closely to the mismatch as possible. They provide an impedance which is of the correct magnitude and opposite reactance phase to cancel the mismatch. The rings, known as slugs, are silver brazed in place on the inner conductor after positioning. Waveguide components are tuned, when necessary, using a similar technique. Small capacitive domes, known as buttons, are placed on the broad wall of the guide. Residual mismatches are cancelled by proper sizing and location of the buttons. Care must be used when tuning components, both coax and waveguide, to insure that the bandwidth of the device remains wide. Tuning methods can never replace the benefits of proper low VSWR component design.

System sub-assemblies are built and tested following component checkout and tuning. Diplexers, filters, switchless combiners, and hybrid combiners are some considered sub-assemblies. They are parts of an overall RF system. Each is tested and adjusted for the desired performance. Measurement of insertion loss, isolation, and group delay must be made in addition to impedance. Diplexer cavity tuning, a complicated procedure, is aided by the analyzers dual measurement capability. The simultaneous monitoring of two of the diplexer outputs with a single input shows the load port and visual port isolation together. Figure 3 shows the visual input insertion loss, impedance and aural input impedance for a typical diplexer.

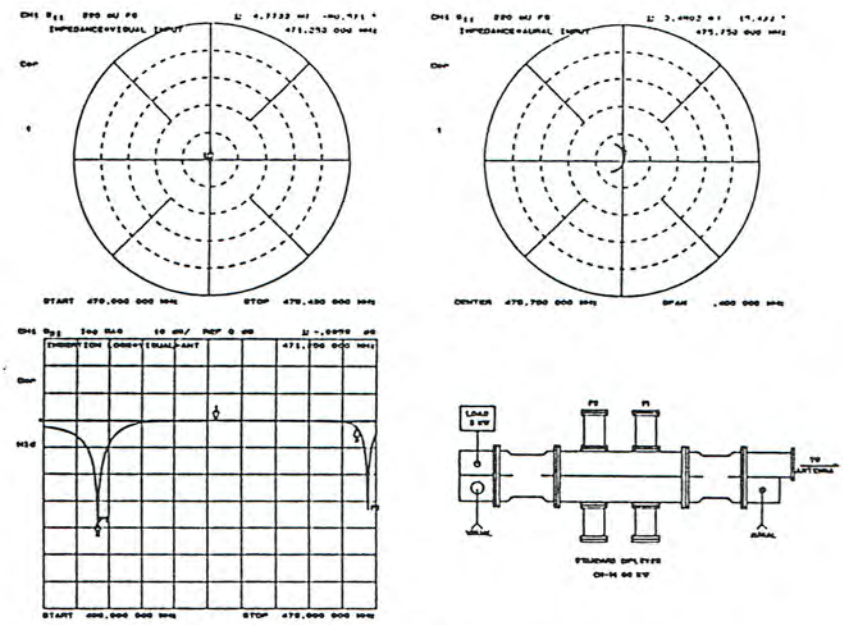

FIGURE 3
TYPICAL DIPLEXER IMPEDANCE AND VISUAL INSERTION LOSS

The final step in the production measurement cycle is to assemble and test the entire system as it will be installed at the station. Systems are shipped assembled as unitized systems or match marked and disassembled for shipping. The system check insures correct operation in all possible modes. A four plot per page output format reduces the number of pages in the final data report supplied with every system. The system performance and signal routing in all operating modes is included in the report.

Recent proposals for advanced concept television (ACTV) have indicated that stringent diplexer and RF system specifications are necessary. Group delay and VSWR variations may be extremely detrimental to video quality, defeating the purpose of enhanced definition. Study of RF system effects has already begun on several proposed methods. New schemes may be required to carry the signal from the tube and radiate it properly without distortion.

FIELD MEASUREMENTS

Recent increases in broadcast plant output power have increased the necessary number of output tubes. It is imperative that maximum power output be maintained under all fault conditions. Concurrently the RF system switching, combining, and routing requirements have become very complex. This increased complexity makes it difficult for the average station engineer to install, adjust and repair the RF system. It is often advantageous, both economically and technically, to leave RF system tasks to the manufacturer's field engineers. The economic advantages result from the field engineers dedication to the RF system only. Trained and experienced in the proper operation of the equipment, he can quickly and correctly locate problems and supervise installation. It is unnecessary for station personel to become RF system experts, a costly undertaking. Since the field engineer brings along his own test equipment and transistions no station equipment expenditures are needed. The technical advantages result from essentially the same things. The experience gained from the completion of many successful installations leads to a system which operates efficiently and requires little maintenance. A poorly installed and adjusted system costs money for maintenance. It may also continuously cost money by being mistuned and inefficient. (Table I)

Field measurements and services available to the broadcaster cover both inside and outside transmission systems. All measurements are made using the network analyzer and associated test transitions.

They consist of:

A) Check and tuning of inside system modes, VSWR, isolation, insertion loss, and group delay.

B) Check and tuning of single or multi-channel coax and waveguide transmission lines with or without the antenna using time domain analysis.

C) Tuning of antennas either at the input or through a transmission line using TDR.

D) Complete system evaluation from the tube output to and including the antenna.

E) Clean, repair, and refurbish any faulty components found in the system and check.

F) All types of field strength measurements.

	VSWR	LOST POWER DUE TO VSWR MISMATCH (kW)	INSERTION LOSS (dB)	LOST POWER DUE TO INSERTION LOSS (kW)	LOST POWER IN REJECT LOAD (kW)	TOTAL LOST POWER (kW)	COST PER YEAR @ 10¢/KWH
WELL TUNED SYSTEM	1.03:1	.056	.09	5.026	.076	5.158	$ 4,518
POORLY TUNED SYSTEM	1.13:1	.882	.19	10.732	2.400	14.014	$12,276

COST PER YEAR
OF TUNED VERSUS MISTUNED
240 kW RF SYSTEM

TABLE I

Transmission line testing and tuning benefit the most from analyzer technology advances in comparison to other system measurements. Two major problems have always made accurate tuning of long lengths of coax or waveguide difficult. First, the poor performance of the input transitions or test equipment often shadowed the performance of the line beyond. Second, the location of mismatches along the line could not be determined close enough to allow their removal. The introduction of error correction and a new technique of line pulsing, known as TDR, have cured these problems.

Error correction helps solve the first of the problems. TDR helps solve both of these problems. Using time domain reflectometry (TDR) a graph of the mismatches on the line versus distance is displayed. Line pulsing is not new for testing broadcast antennas[1] however, old techniques required a large amount of equipment and interpretation. Modern TDR uses the analyzers digital data format and built in computer to generate the response. An inverse fourier transform (FFT) is used to calculate the time domain response from standard frequency response information (VSWR, insertion loss). For narrowband devices the bandpass time domain response must be obtained. This is used when the devices response is correct only over a small frequency range. The mismatch values averaged over the frequency range selected are displayed versus time. The location of the mismatch is then easily determined. Distance resolution is determined by the frequency span of the measurement. Wider bandwidth yields higher distance resolution (Table II).

MEASUREMENT FREQ. SPAN (MHz)	DISTANCE RESOLUTION (ft in air)
6	41.0
20	12.3
50	4.9
100	2.46

TDR
SPAN VS RESOLUTION
TABLE II

Because the time scale is mathematically derived, any desired display increment can be selected. The line can be examined in detail or a top to bottom view can be displayed. By mathematically removing or gating out a portion of the line and converting back to the frequency domain, the VSWR or insertion loss without that portion is obtained. Gating is used to remove input and output transitions from the measurement. Solving the first problem mentioned above. By removing everything but one response we can measure a single device. An antenna can be measured from the base of the tower without disconnecting it from the transmission line.

The TDR is now used for all transmission line tuning. It has become an irreplaceable tool for locating line difficulties. Loose flanges, dents, and other assembly problems can be easily found. On a recent job it was even used to find a connection where, instead of one, two gaskets were installed. Single channel operation dictates that the line and antenna have very low VSWRs over a six MHz band. This results in a resolution of 41 feet, a distance too great to locate problems. Bandwidths of 20 or 50 MHz yield resolutions good enough to pinpoint problems on long runs. These bandwidths maintain the necessary narrowband restriction. Two TDR measurements are therefore made. One over six MHz to determine the magnitudes of the reflections in the desired channel. A second measurement over a 20 or 50 MHz band is used to locate the positions of the mismatches. The magnitudes of the wideband measurement are used for reference only. Figures 4 and 5 show six MHz and 50 MHz TDR data obtained on a recently installed 1000 foot waveguide run and side mounted antenna on Mt. Sutro in San Francisco, CA. This line included several sets of odd angle elbows, offsets and twists. From the 50 MHz data we can locate mismatch areas. Comparing the antenna response in figure 4 to that in figure 5 shows the effect of widening the bandwidth on the measured mismatch magnitude. The average antenna VSWR which appears at approximately 2.6 s, over six MHz is very low (<1.03). The antenna average over 50 MHz is much higher (1.40),

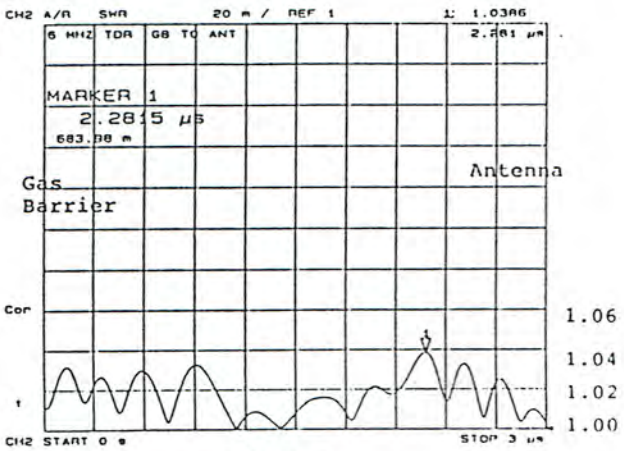

FIGURE 4
WAVEGUIDE AND ANTENNA VSWR
6 MHz TIME DOMAIN

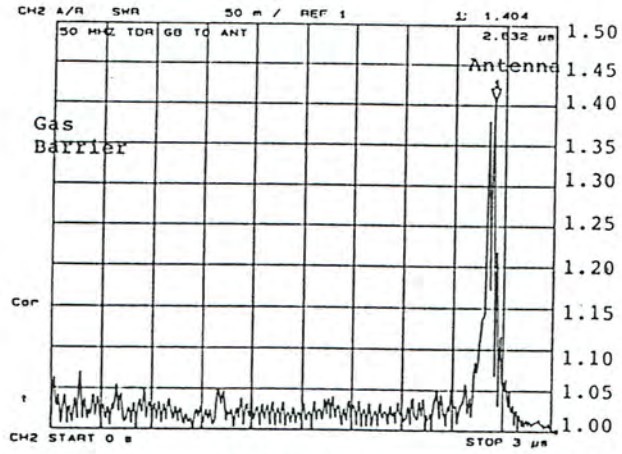

FIGURE 5
WAVEGUIDE AND ANTENNA VSWR
50 MHz TIME DOMAIN

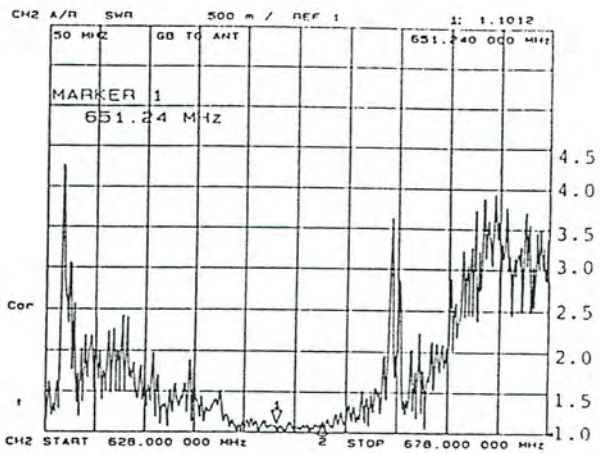

FIGURE 7
WAVEGUIDE AND ANTENNA VSWR
50 MHz FREQUENCY DOMAIN

showing how narrow it's tuning is. Figure 6 shows the six MHz data in the frequency domain format. The line and antenna have a VSWR less than 1.13:1 over the band. The 50 MHz frequency domain data in figure 7 shows the relatively narrow system VSWR performance which results.

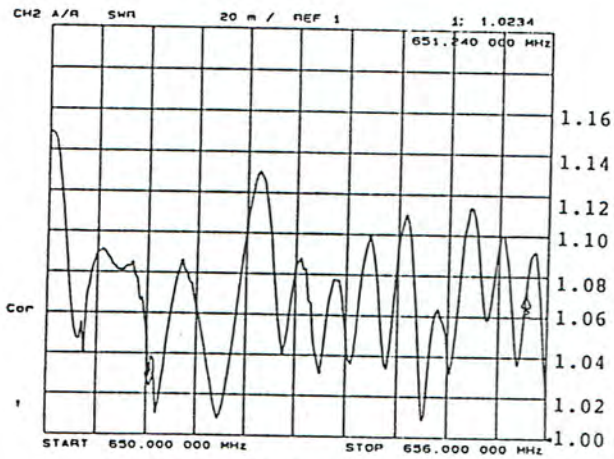

FIGURE 6
WAVEGUIDE AND ANTENNA VSWR
6 MHz FREQUENCY DOMAIN

The recent introduction of high power UHF dual channel installations[2] in the US and abroad has led to another new measurement technique. In the past the tuning of dual channel systems was done by sweeping the entire bandwidth necessary to cover both bands. Markers were placed on the carriers and these points were optimized. Since it is difficult to tune one channel without effecting the other, broadband sweeping was the only answer. The analyzer has made dual channel tuning simple. Two separate narrow measurement channels can be set up and displayed simultaneously. The effects of line tuning are shown on both channels together. Two TDR plots can also be displayed. This technique was used on a 240kW dual channel 1200 ft. dual waveguide system in Kuwait. The broadband return loss data obtained after tuning one of these lines is shown in figure 8. The line VSWR is less than 1.10 over approximately 30 MHz. Dual channel combining system alignment is also simplified with this technique. The response of the two input channels can be obtained by feeding the antenna port with a single cable.

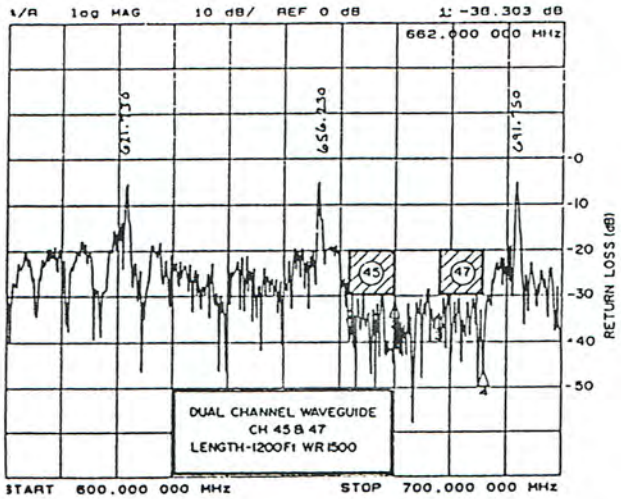

FIGURE 8

CONCLUSION

RF system measurements during manufacture and in the field have benefited from the introduction of vector network analyzers. Several techniques used for these measurements have been presented. The advantages to the station engineer of good RF system performance have also been demonstrated.

The analyzer accuracy discussed will be necessary for the next generation of ACTV/HDTV RF equipment.

References

[1] M.S. Siukola, "TV Antenna Performance Evaluation with RF Pulse Techniques", IEEE Trans. On Broadcasting, Vol BC-16, #3, Sept. 1970

[2] J.T. Stenberg and E.H. Mayberry, "UHF Multichannel Television Antenna Systems", 1987 NAB Conference Proceedings, pg. 313