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NAVY SHIPBOARD WAVEGUIDE SYSTEM INSTALLATION

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ABSTRACT - This paper describes how one Naval Shipyard reduced from months to one week the time to test, fix and certify shipboard waveguide runs up to 160 foot long. It also shows how further improvements can be obtained. The recommendations offered here apply to most large waveguide systems.

1. Introduction

This work began with a request from the shipbuilder, Bath Iron Works (BIW), for consulting help. They couldn't meet what they felt was a reasonable specified VSWR value into a standard load with their microwave test equipment. No waveguide runs would pass the first time, and rework to finally pass was taking months. Although filled with pride, the shipbuilding management was willing and eager to learn better methods.

Formally the author acted as a consultant to LORAL Federal Systems (then IBM Federal Systems Division) to isolate production and test equipment deficiencies in the waveguide systems aboard U. S. Navy ships that they support for BIW. Another objective was to share test methods with Navy Engineering Personnel from the Naval Air Warfare Center Aircraft Division (NAWCAD).

The subject of the work was the build and test of long waveguide runs (up to 160 feet) installed in the AN/SRQ-4 Data Link Subsystem of the LAMPS (Light Airborne Multipurpose System) MK III System. The waveguide subsystem examined was installed in destroyer DDG-56, the USS John S. McCain, and ran from the radio transmitter room to an antenna on the mast. The Data Link supports communication between the ship and an SH60B Seahawk Helicopter. The waveguide is WRG-95, MILW-85 1 by 2 inch waveguide tested for input Voltage Standing Wave Ratio (VSWR) and for insertion loss over a frequency range within G-Band.

This paper begins with the findings from an on-site tour, then proceeds through an analysis of installed waveguide measurement error to show that it is possible to build waveguide runs that will pass final test without rework at least 90% of the time. It then gives the system, test and process recommendations required to achieve this performance. The recommendations that have been implemented to date are then described. The report concludes with a description of the benefits achieved thus far, what more can be implemented and what further benefits can be expected.

2. Findings.

Dent-tuning of the installed long waveguide runs was being suggested in order to pass the final test for VSWR on board ship. Dent tuning is the process of optimizing electrical performance by making strategically placed dents in the waveguide. It has a legitimate place in the construction of individual pieces of waveguide if done under very controlled conditions. However, it would have created great logistical problems if used in tuning long runs of 20 or more sections, where one or more sections would have to be replaced later. And the process itself is usually performed on sections open at each end using a small steel ball inside the waveguide. The ball is maneuvered by a magnet outside the waveguide to find the right place for the dent. This process would be impossible on a long shipboard run. An alternative would be making dents "just to see if it helped". Dent tuning of the final assembly was deemed neither desirable nor necessary.

Rather, the key finding upon visiting the shipyard was that waveguide fabrication and waveguide test were separate and unrelated operations. The waveguide shop fabricated the required sections of waveguide to mechanical and metallurgical quality specifications. The personnel there were highly skilled craftsmen who were meeting very stringent quality requirements, but without electrical waveguide section test they had no knowledge of what a good job holding dimensional accuracy and surface finish was doing for electrical performance.

Waveguide test was performed from the radio transmitter room on board the destroyer on the completed waveguide run. Test results at this high level of assembly could not guide the fabrication craftsman to best electrical results from their work. Waveguide fabrication and installation may be primarily a mechanical task resembling plumbing and pipefitting, but there are electrical considerations that must be taken into account. So it was clear that the quality of the work of the people was excellent, that was no problem. The people needed to be provided with more accurate measurement tools and a system so that they could confirm their quality work. The test equipment was not sufficiently accurate to support measurements at the waveguide section level.

So the basic problem was in test. Once that was solved, then the rest of the solution would be to form a system and processes around the new capability.

There were two basic problems in test. One was of accuracy: the VSWR specification of 1.25:1 was being measured on a measurement set whose readings on a precision waveguide load were typically 1.1:1. This was not good enough. To measure 1.25:1 the measurement set should have been 10 times better: equivalent to a 1.025:1 maximum VSWR into a precision waveguide load. And further, to measure the individual pieces (1.05:1 VSWR for straight runs, 1.08:1 VSWR for bends or twists) the maximum error should similarly be 1.005:1 to 1.008:1.

The other basic problem in test was that swept frequency VSWR did not localize which sections of waveguide had to be replaced. A Time Domain Reflectometer (TDR) function was needed to perform that needed radar-like function. The shipbuilder didn't have this TDR equipment, but was able to borrow it on occasion from NAWCAD.

3. Installed Waveguide Measurement Error.

The following worst case and probabilistic 3σ VSWR error analyses show that 22 sections of waveguide could be combined to produce 1.25:1 specification performance first try without rework in most cases. The key is manufacture of the waveguide sections to a sufficiently tight (but not excessively tight) tolerance. This means manufacture to a statistical requirement that allows for a certain percentage of rework at final test, rather than to a worst case specification.

Given k sections of waveguide of VSWR ρ_l, and m sections of waveguide of VSWR ρ_n, then the worst case VSWR ρ_{wc} is represented by the equation [LIA80]

$$(\rho_l)^k \times (\rho_n)^m = \rho_{wc} \tag{1}$$

For ρ_l = 1.05 VSWR, ρ_n=1.08 VSWR, k=12 sections and m=10 sections it follows from the above equation that

$$\rho_{wc} = 3.8 \tag{2}$$

the worst case VSWR is 3.8:1 for the total waveguide run and way over specification. To assure that the product of 22 worst case waveguide sections would be 1.25:1 or better then the worst case VSWR ρ_{wcsect} would have to be:

$$\rho_{wc\,\sec t} = \sqrt[22]{1.25} \tag{3}$$

or ρ_{wcsect}=1.01:1, an unattainable number for a waveguide section in production at reasonable cost. Therefore, to design a system for the worst case conditions would be unrealistic.

A 3σ analysis will yield a probabilistic value $\rho_{3\sigma}$ of VSWR that will be more realistic. The calculation is based on three assumptions. The first assumption is that each waveguide section has a normal distribution of error with the specified maximum error being 3σ, 3 times the standard deviation σ of the assumed normal distribution. The 3σ value is met 99.74% of the time, where the maximum value is met 100% of the time.

The second assumption is that the value of the error has an equal probability of being + or - so that the mean of the error distribution is zero. This is met by converting VSWR ρ to reflection coefficient Γ. The value of Γ has an equal probability of being + or - (or any phase) so that the mean value of is zero. The transmission line reflection coefficient Γ is the amplitude (magnitude and phase) of the wave reflected undesirably off a mismatched section of waveguide. That amplitude is normalized to the amplitude of the input wave to that section. It is this reflected wave that produces the VSWR ρ by constructive and destructive interference [LIA80]:

$$\Gamma_{l3\sigma} = (\rho_l - 1) / (\rho_l + 1) \tag{4}$$

$$\Gamma_{n3\sigma} = (\rho_n - 1) / (\rho_n + 1) \tag{5}$$

The third assumption is that the reflection coefficients of the waveguide sections are not correlated.

Under these assumptions, the aggregate 3σ reflection coefficient $\Gamma_{3\sigma}$ for the total waveguide run for is [OLK80]:

$$\Gamma_{3\sigma} = \sqrt{\sum_{u=1}^{n} \Gamma_{u3\sigma}{}^2} \tag{6}$$

and for n = k + m reflections is:

$$\Gamma_{3\sigma} = \sqrt{k\Gamma_{l3\sigma}{}^2 + m\Gamma_{n3\sigma}{}^2} \tag{7}$$

which converted back to VSWR $\rho_{3\sigma}$ is:

$$\rho_{3\sigma} = (1 + \Gamma_{3\sigma}) / (1 - \Gamma_{3\sigma}) \tag{8}$$

If all the assumptions were correct, then the result of applying the above equations would be a value $\rho_{3\sigma}$ of VSWR that would be met for 99.74% of the waveguide runs.

For the input numbers of the previous case $\rho_{3\sigma}$=1.35:1, which is much closer to specification than the worst case value of ρ_{wc}=3.8:1. This says that if the individual pieces of waveguide meet specification, then 99.74% of the systems consisting of these pieces assembled in series will have a VSWR of 1.36:1 or less with no rework. Similarly, the same equations (4) through (8) can be used to show that if each of the 22 sections has a 3σ VSWR of 1.05:1, then $v_{3\sigma}$=1.25:1.

One can argue about the validity of the assumptions, but experience suggests that for at least 90% of the waveguide runs no rework at all will be needed. The significance of these calculations is that it is possible to take good advantage of proper control on the VSWR of the individual waveguide sections. One can create 22-section waveguide runs on a ship, most of which will pass a 1.25:1 VSWR the first time without rework.

4. System Recommendations.

The shipboard waveguide run should be defined as an electrical subsystem just as is the antenna assembly at one end up on the mast, or the data link receiver/transmitter subsystem at the other end. The individual waveguide sections should be made to an electrical maximum VSWR of 1.05:1 or less for a 22 section run with 1.25:1 VSWR for the assembly. It then should be expected that less than 10% of the waveguide runs will need rework if installation has been performed carefully enough to preserve the performance of the individual waveguide sections.

To permit the waveguide VSWR measurement accuracies necessary, calibration should be performed in the waveguide itself, not the coaxial system feeding the waveguide. Waveguide calibration kits contain a precision load, shorting plate and extended short and can provide a very accurate s11 calibration. Hewlett/Packard [HPC95] should recommend the test equipment and methods for achieving the required accuracies for a specific case. For measuring the specified top level assembly 1.25:1 VSWR, the error with the precision load in place should be less than 1.025:1, and for measuring the specified waveguide section 1.05:1 VSWR the error should be less than 1.005:1.

In the event that a run is out of specification, the test equipment should include a Time Domain Reflectometer (TDR) function in order to find which waveguide sections in that run needs to be replaced. The TDR will point to the location of a waveguide section with a high VSWR defect. The TDR function must be derived from a set of swept frequency network analyzer measurements. The more traditional D.C. pulsed TDR will not work for waveguide because the waveguide low frequency cutoff characteristic will not permit a D.C. pulse to propagate.

5. Test Equipment Recommendations.

The Hewlett/Packard 8720C or 8510 automatic network analyzer with type N coaxial Gore (TM) dielectric cables connected to a type N to WRG-95 waveguide adaptor are recommended to perform both the VSWR and the TDR function. With the addition of a shorting plate at the far end of the waveguide then the attenuation may be computed as half the value of the measured return loss. BIW chose the more portable 8720C to fit through the spaces of the ship.

The waveguide calibration kits used for this task may be purchased from Microwave Development Corporation [MDC95]. The kit cost is $4,500 as of this writing. With this kit the reflection coefficient ρ measurement uncertainty is ρ =.007 [MAN92], and the corresponding VSWR into a matched load using equation (8) is 1.014:1. This is not the more ideal 1.005:1, but is representative of the state of the art today in production test equipment.

One can perform a partial waveguide calibration by using the coaxial cable short-open-termination calibration method, with the coaxial to waveguide adaptor with waveguide termination substituted for the coaxial termination. This will correct the effects that the coaxial to waveguide adaptor have on directivity, and will improve the results somewhat. However, directivity is only one of three sources of error. The other two are source match and frequency response, and these two sources of error are not corrected in this partial calibration.

The frequency response of a well-made adaptor can be expected to be very good and not be much of a contributor to error. The more important contributor to error is the source match of the adaptor, which can range from 1.2:1 to 1.05:1, and is most likely to remain a significant contributor to the measured VSWR of the waveguide. The partial calibration yields misleadingly good VSWR readings like 1.0009:1, which are a measure of the repeatability of disconnecting and reconnecting the adaptor and the termination, not the accuracy of the measurement. Using the partial calibration may save the cost of the calibration kit, but it is a false economy for at least two reasons:

1. More waveguide runs will fail specification because the measurement system will contribute unnecessary error. Just one failure due to partial calibration could justify the cost of a calibration kit, because of the labor cost of unnecessarily reworking a waveguide run.

2. It will be impossible to measure individual waveguide sections with sufficient accuracy. That whole process is not supported by partial calibration.

6. Process Recommendations.

More than new equipment is needed to solve the problems on building specification compliant waveguide runs. The equipment must be part of a controlled process that quickly and cheaply produces a quality product. This is a process that is in control in the statistical quality control sense of W. Edwards Deming [GIT89] There should be in-process electrical measurement right in the waveguide fabrication shop, and the results should be statistically analyzed for common and special variations, which in turn should be used to initiate root cause analysis. Root cause analysis would be used first to eliminate special variations (sometimes called “flyers”) to bring the process under statistical control, then to reduce statistical variation. This is not the fancy process that it may sound like. It means getting away from relying on mechanical inspection with no ability to tie the results to electrical performance. It means putting a formal process in place to improve the product to the levels needed, then maintaining that process for the life of manufacture.

It is characteristic of this methodology that the need for test diminishes over time as the right in-process controls are implemented. This will happen in both waveguide section fabrication and waveguide run final test.

7. Recommendations Implemented to Date.[1]

At BIW the methodology currently implemented is to install the waveguide, test then fix the bad sections as follows:

1. Build all waveguide sections to specs, with no electrical test or tune.

2. Assemble and install them on the ship.

3. Measure VSWR with a partial waveguide calibration and usually fail.

4. Perform a TDR measurement to find the worst 2 or 3 sections of waveguide.

5. Remove those sections.

6. Replace the sections outright, or test and tune them in a controlled 2-port s-parameter measurement environment and then replace them.

7. Reassemble the waveguide run and retest.

After one cycle through the above process the waveguide run will usually pass1.25:1 VSWR with an insertion loss under 4.5 db. In the event that the waveguide run fails to pass, repeat the TDR measurement and succeeding processes.

8. Conclusion.

Having the right test set and partial waveguide calibration techniques is already producing a large time savings to the shipbuilder. Where it used to take months to test and fix a waveguide run 160 feet long to pass 1.25:1 VSWR, it now takes only a few days to a week. With the partial calibration, the TDR measurement can show more clearly where the faulty waveguide sections are.

The results attained thus far at BIW are excellent, but they only partially realize the cost reduction potential for these waveguide systems. The shipbuilder can further reduce time and cost. Also, the recommendations offered here apply over most U. S. Navy waveguide systems. BIW itself could use them on other waveguide systems besides LAMPS MK III.

At this point in the shipbuilder’s progress toward application of the recommendations there is an attainment of significantly lower cost at better confirmed quality. However, with a full calibration (rather than only a partial calibration) more systems could be expected to pass on average because the measurement equipment would contribute less error. If there is something in the partial calibration that compensates for a consistent defect in the waveguide, then quality is suffering.

The current partially calibrated test equipment should not be expected to be accurate enough to control the manufacture of 1.05:1 maximum specification waveguide sections. So today it is reasonable that the shipbuilder does not perform electrical test and tune at the waveguide section level. But tomorrow is a different story. For six years build quality has been in place at BIW, but with the systems, tests and processes that are in place, that quality can’t be fully proven. All visible waveguide defects have been removed, but still the final assembly doesn’t pass first time VSWR test as often as it could. If full calibration is instituted, then with the increased accuracy of the test set it will be possible to inaugurate a process that includes electrically sorting out and tuning at the level of shipyard craftsmen building the individual waveguide sections. These craftsmen have been building metallurgically excellent, but subtly physically distorted sections. These subtle distortions are

1. See Section 9, Acknowledgments.

among the remaining targets for improvement. The amount of waveguide section test required should be expected to drop over time as in-process controls are put in place that consistently produce specification-compliant parts.

Improvements in the test equipment are not all that remains. This work sets the stage for the improvement of quality starting with control charts, pareto diagrams and cause and effect diagrams based upon electrical measurements at the waveguide section level. With the improved test equipment, the craftsmen can self-help with electrically-based trend analysis. This will permit ownership, empowerment and self-assessment by the craftsmen.

As a result of this consulting relationship, the team at BIW has experienced improved morale about themselves and their work.

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Mr. John P. Daley, Bath Iron Works, Mail Stop 2390, 700 Washington Street, Bath Maine 04530. Telephone (207) 442-2197.

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