AM Directional Arrays — What to Do When They're Broken

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Introduction

In this, the Digital Age, the AM directional array still proliferates as a necessary transmission tool in the broadcast industry. The pool of engineers trained to work on these often complex and difficult-to-understand antennas has dwindled due to attrition, retirement and other causes, leaving many AM directional stations without an AM DA-trained engineer. When a problem arises with the array, the station engineer may be ill-equipped to deal with it. In this paper, I will present practical methods of troubleshooting and repairing a directional antenna that will prepare an engineer without significant AM DA experience to work on the array with confidence.

1.0 Introduction

Consolidation is definitelty the way things are going these days. It seems the individual radio station owner has become something of a rarity. Large group owners are buying up stations even in the smaller markets. On the engineering front, we have had to adapt. The old "one station, one engineer" way of doing business is long gone, replaced first by the contract engineering trend in the 1980s and today with economies of scale. One chief engineer may well be called upon to care for four or more co-owned stations in a cluster or even in adjacent markets.

While this makes a lot of sense in many ways, quite often the station engineer may find himself responsible for one or more AM directional facilities for which he is ill-prepared to deal. Those engineers that spent their careers building, tuning and nursing DAs have, in large part, retired, leaving a new generation to try and figure out what's going on. The day that one of these arrays goes out of whack can be a day of dread and stress unless the engineer has a plan for dealing with the problem *when* (not *if*) it occurs.

In this paper, it is my intention to give the engineer that finds himself in this unenviable position some tools that he can use to diagnose and repair an ailing array. I hope that this information will remove much of the mystery, dread and fear that may accompany directional antenna work by the uninitiated.

2.0 Rule #1: Don't Panic

When a directional array goes out of adjustment for whatever reason, the tendency is to grab phasor controls and try to correct the situation immediately. Make no mistake: this is the wrong thing to do! *Don't touch anything* until enough information has been gathered to make an educated decision of *what* to do.

While directional arrays are often mysterious, difficult-to-understand beasts that can make little sense to the uninitiated, the same physical and electrical principals that apply to the transmitter, mixer and CD player also apply to the directional array. The directional array should be viewed as an electrical device just like any other that you may be called upon to service.

With that in mind, when a problem arises, the engineer should ask the same questions that would be asked when approaching any troubleshooting task. He should gather information in a systematic manner, objectively and calmly analyze the information and make decisions based upon what he knows.

3.0 Test Equipment

There is a certain complement of test equipment that should be on hand for the maintenance, troubleshooting and repair of any directional array. When the consulting engineer comes to town, he may bring a truckload of gadgetry. While it is nice to have all these test instruments, a much more modest set of test gear will do in most cases. If it is not practical to purchase this equipment, one would do well to locate it at other stations in the market from whom it can be borrowed or rented.

The Delta Operating Impedance Bridge (OIB) is the most important piece of test equipment for the engineer working on a directional array. This device permits in- or out-of-circuit measurements of resistance and reactance. The OIB can handle up to 5 kW of power. From time to time, OIBs can be found on the used market.

The OIB can also be used in an out-of-circuit mode for static resistance and reactance measurements. To do this, an oscillator or signal generator is needed to drive the OIB and a receiver or some sort of detector is needed.

Ideally, one would have a Potomac SD-31 synthesizer/detector or Delta RG-4 receiver generator on hand to use with the OIB as both oscillator and detector. If there is a budget for such a device, it would be worthwhile to obtain one.

There are, however, plenty of high-quality test oscillators and signal generators on the used market that will drive the OIB just fine. These are available at flea markets, swapfests and from used test equipment dealers. The only requirements are reasonable frequency stability and a low-impedance output.

Just about any general coverage receiver with an input attenuator and an S-meter will work as a detector. A receiver with a built-in beat frequency oscillator (BFO) is particularly handy for this application. Perhaps the best compromise for a detector, however, is the station’s field intensity meter (FIM). It is well-shielded, has a meter with multiple scales, has an accurate frequency dial and is battery operated. Since every directional station license contains a requirement to have field strength measurement equipment available, a field intensity meter should be accessible.

Finally, an RF ammeter of known accuracy capable of giving an on-scale indication of any base current in the system and the common point current is an excellent diagnostic tool to have on hand. A junk-box thermocouple ammeter is fine for this application if it is calibrated against another ammeter of known accuracy. Keep in mind that if there are nonlinearities in this meter, there is nothing wrong with making and using a calibration chart. The idea is to be able to measure current and verify the accuracy of other meters in the system when a problem arises.

4.0 Specific DA Problems

While it is impossible to anticipate every failure mode, problem or symptom that may arise in a directional antenna system, there are many common problems that can be addressed specifically. The troubleshooting and repair principles that apply to the cases discussed herein will quite often apply to other situations as well.

4.1 Incorrect Antenna Monitor Parameters

From time to time, the operating parameters as indicated by the antenna monitor may be incorrect. When this occurs it is best to start by making a note of the proper values on a piece of paper with the values as read on the monitor alongside. In this way it can be quickly determined which parameters are at variance. If only one or two values are at variance while all the others are normal, there is a good chance that the problem is with the sampling system or antenna monitor. In this case, the array is likely to be functioning normally.

As a rule, when something changes in an array due to a component malfunction, all the parameters are affected to some degree. This is because of the mutual coupling between the array elements. When cranking the phase of one tower a couple of degrees while touching nothing else, it is likely some change will be observed in all the other phases, ratios, base currents and the common point resistance/reactance as well. When a parameter change occurs in a directional array, in addition to determining if all the antenna monitor parameters have changes. the common point current and impedance should be checked. If a change has occurred there, it is likely that there is a real problem with the array; if it hasn't, the antenna monitor or sampling system is likely at fault.

4.11 Faulty Antenna Monitor

If only *some* of the antenna monitor indications have changed without a change at the common point, the monitor can often be checked by swapping inputs to the monitor. A common failure mode in some antenna monitors is a stuck relay. The mercury-wetted relays in these units should be trouble-free and long-lived but they tend to wear out over time. When a relay sticks, it may cause all the indications for all the towers but one to be incorrect. To check for this, disconnect all inputs but the reference tower, then connect one of the other tower sample lines to each of the other inputs in turn. A normal indication of phase and ratio for the sample line being used should be displayed on the monitor as it is moved from input to input. When a channel is connected where the correct readings are not displayed, that is often the one with the bad relay. If there is a stuck relay, it tends to load the other channels so while the phase readings may be normal during this procedure, the ratio readings will often be low for all <u>but</u> the channel with the defective relay.

Occasionally, antenna monitor sample line terminating resistors can become damaged by arcs or lightning strikes. The symptom will be a very high ratio on one of the antenna monitor channels. Check these resistors with an ohmmeter. It is also a good idea to check the operating temperature of the load resistors under normal conditions. One or more very hot resistors may indicate that the amplitude of the sample for those towers may be too high for the monitor.

The detector diode in the antenna monitor is one of those "future failure components" to watch out for. Usually this diode is a germanium type, very prone to damage from lightning. If this happens, hopefully it will open completely. Occasionally, the failure mode is partial opening with some observed resistance in series. This produces a non-linear condition that will cause incorrect ratio readings on all towers. The symptom of this condition will be a significantly changed loop reference setting on the reference tower. If it is necessary to crank that control more than half a turn to get 100% on the loop meter with normal power output from the transmitter, suspect the detector diode. A good check is to log the normal turn counter reading on the loop reference control for each mode. Significant deviation from this setting to achieve a 100% loop reference reading is cause for further investigation.

4.12 Faulty Sample Line

Another possibility is a faulty sample line. Sample lines can be checked by running an open circuit/short circuit impedance test on them. This will yield the characteristic impedance and approximate electrical length of each of the lines. You can also bridge the sample lines open-circuit at a quarter-wavelength resonant frequency to determine exactly the electrical length. The procedures for measuring open circuit/short circuit impedance and electrical length are discussed in the section on transmission lines.

If you have access to one, the best way to check sample lines is with a time-domain reflectometer (TDR). These devices are generally available for rent, and many tower riggers now have TDRs in their shops. If your bridge measurements indicate a sample line problem, the TDR is the best means to physically locate the fault. Keep in mind that sample lines in a directional system are usually equal length and the excess line for the closer towers is usually buried. Before digging, it is wise to use the TDR to locate the fault from both ends unless the location of the buried excess is known.

4.13 Sample Loops/Transformers

Sample loops can cause trouble, with welds and insulators breaking. Sometimes high winds can blow loops around so that they are no longer properly oriented. A sample loop should be positioned so that it is perpendicular to the tower face behind it. A good way to check loop alignment is to stand at the tower base and look up at the loop. A properly positioned loop should line up with the guy wire. Loops should be inspected up close, looking for corrosion, loose connections and hardware. Most loops attach to the sample line with an N- or UHF-connector of some sort. These connectors should be inspected for water, corrosion, and tightness. There may be a copper strap or braid used to jumper from the connector to the open end of the loop. This strap can easily break loose from the loop. It should be checked for proper bonding to the connector and to the metal of the loop.

Toroidal sampling transformers can, from time to time, cause problems. Some are prone to arc internally when their output is unloaded. While sample lines should always be terminated into the load resistors in the antenna monitor, it is possible that enough voltage could develop at the tower end of a long sample line to allow an arc to occur. If a transformer is suspect, it can be swapped with one from another tower (any but the reference tower) to see if the problem disappears.

4.2 Incorrect Base Currents

The most suspect indicating instrument in any radio station is the RF ammeter. From the moment it leaves the factory its calibration becomes suspect.

Vibration, magnetic anomalies, temperature, humidity, insects, moisture — everything — affects its accuracy. Toroidal current meters can also lie but are generally more reliable than thermocouple meters.

If a base current ratio indication is wrong and everything else is okay (antenna monitor parameters and monitor points), the accuracy of one or more of the meters should be suspected. The calibrated RF ammeter mentioned in the discussion of test equipment should be installed in place of the suspect meters, one at a time, and the indication noted. If there is a meter problem, it should be readily apparent.

In the case of loop-sampled towers, base currents will quite often change without a corresponding change in the loop current. The phasor controls can sometimes be adjusted to bring the base current back into tolerance, but this is often at the expense of running a loop ratio out of tolerance. There are times when, due to environmental changes, the base current ratios in an array will drift out of tolerance with everything else dead-on. If this happens, the best thing to do may be to obtain a special temporary authority (STA) from the FCC to allow operation at variance from the licensed parameters for a period of time. This will buy you time to observe the base current ratios to see if they go back where they belong, which they may well do when environmental conditions change once again.

At the time of publication, there is a rulemaking proceeding underway at the FCC which, among other things, deletes the requirement to maintain base current ratios. If this rule change is enacted, it will remove this burden altogether.

4.3 High Monitor Point

A likely cause of a high monitor point reading is an anomaly at or in the vicinity of the point itself. Reradiators and other factors beyond the station's control can influence the field strength at a monitor point. If a point is found to be high, it is important not to adjust anything. The field strength at five or six points should be measured on the radial to determine how they compare to the last full or partial proof. If the points measure at or below the proof field strengths, you can assume the array is in adjustment and the monitor point itself has become unusable. §73.158 specifies the procedure for changing the monitor point on a radial.

If the entire radial is high, the array may be out of adjustment, even though the array parameters are all within adjustment. This can easily occur in arrays with very tight nulls.

Before any adjustments are made, it is a good idea to put the array in the non-directional mode and measure the field strength at five or six points along the radial both ND and DA. The ratios should then be compared with those in the last full proof. It could be that a conductivity change is responsible for the high readings and the array is in adjustment.

A condition where some points on a radial are found to be high and others quite low may indicate the presence of a standing wave. This usually indicates that reradiation is present. At this point, a search should be made in the main lobe or other areas of strong field intensity for a new or altered tower, monopole or other structure that may be reradiating. Objects in null areas or other areas of low field intensity will seldom receive enough energy to reradiate significantly.

To determine whether an object is reradiating, the procedure is to locate a point at which the potential reradiator and the directional array are at right angles to one another. The field strength meter is then used to determine if a solid null can be obtained by rotating the antenna perpendicular to the directional array (but toward the reradiator). If a solid null, 10% or less of the on-axis reading, cannot be obtained, it is likely that the object is reradiating and detuning may be required.

Once the reradiator has been located, the services of a consulting engineer may be required to measure the actual effects and chart a course of action. If the object is a tower or monopole belonging to an FCC licensee, that licensee may well be obligated to detune the object and conduct proof measurements on your array at his expense.

If a radial is found to be high and the cause cannot be traced to reradiation, the best course of action is to get some help. A consulting engineer or someone else who has a good bit of experience in tuning directional arrays should be retained to determine the cause of the high radial and bring the array back into adjustment.

4.4 Faulty Component

From time to time, parts do fail in directional antennas. The most common failure component is the mica capacitor. While such capacitors are always suspect, they are not always the problem.

A symptom common to component failure is heat. A good way to find a bad component is to shut the system down and immediately but carefully feel of all the components in the phasor and ATUs. Some components may be warm but none should run hot. Any hot component should be suspect. Discoloration of coils is an indication of excessive heating. Loose hardware can get red hot under current, causing oxidation and an intermittent connection. Leaking capacitors are a sure sign of a problem.

The OIB, signal generator and detector should be used to measure the resistance and reactance of any suspect components. Capacitors and coils should not have any significant resistance and a resistive component in their impedance indicates a problem.

Many stations have the old-style "magic eye" capacitor checkers lying about and these can be used to check suspect capacitors. A capacitor of known value should be used to test the checker before testing the suspect cap. Many of today’s better digital multimeters (some in the under-$100 range) have a built-in capacitor check function, and these can also be used to check suspect capacitors. All capacitor measurements should be made out of circuit, and lead inductance should be taken into consideration.

4.5 Faulty Transmission Line

If all the components in the system look and check okay but the parameters are still out of tolerance, the problem could be a defective transmission line. Water can enter a line and change both the impedance, loss and velocity factor of the line. Bad connections can generate heat and eventually cause a burnout. Arcs can also occur, leading to a burnout.

When a transmission line problem is suspected, a good visual inspection should be performed on all exposed parts of the line. Any evidence of heating (such as a melted jacket) or arcing (soot or pitting) should be investigated. Pressurized lines should be checked for pressure integrity by closing the valve from the pressurization manifold to the line and watching the line pressure gauge.

When there are no external signs of damage to a suspect line, there are some simple bridge measurements that can reveal a great deal of information about the condition of the line. These measurements can be made on any transmission line, including sample lines.

Two measurements are all that are required to determine line impedance: A short-circuit measurement and an open-circuit measurement. The measurements are begun by disconnecting the transmission line to be measured at both ends. With the far end of the transmission line open, the resistance and reactance of the line are measured at a frequency on which the line will be close to an odd number of eighth-wavelengths long. The actual frequency does not matter except that resonant lengths should be avoided. Reactance readings indicated on the bridge should be corrected for frequency. Next, with the far end of the line shorted, the resistance and reactance of the line should again be measured.

With the open-circuit and short-circuit resistance and reactance values in hand, the results are used in the following formulas:

$$Z_{OC} = \sqrt{R_{OC}^2 + X_{OC}^2}$$

$$Z_{SC} = \sqrt{R_{SC}^2 + X_{SC}^2}$$

$$\theta_{OC} = \arctan\left(\frac{X_{OC}}{R_{OC}}\right)$$

$$\theta_{SC} = \arctan\left(\frac{X_{SC}}{R_{SC}}\right)$$

Where: Z_O is the magnitude of the measured impedance of the transmission line

$$Z_O = \sqrt{Z_{SC} Z_{OC}}$$

θ_O is the angle of the measured impedance

$$\theta_O = \left(\frac{\theta_{OC} + \theta_{SC}}{2}\right)$$

Z_{OC} is the magnitude of the measured open circuit impedance

θ_{OC} is the angle of the open-circuit impedance

Z_{SC} is the magnitude of the measured short-circuit impedance of the line

θ_{SC} is the angle of the open-circuit impedance

The angle component of the line’s impedance can yield information about the condition of the line in addition to the magnitude component. If the angle component is high (say, anything over 20°), there maybe a defect in the line causing it to have a high reactance. A perfect line would have a purely resistive impedance, but in the real world we almost always see some reactance. A low angle component of the impedance value is sufficient to indicate that the line is probably okay. Likewise, a high angle should be a clue that there is a problem. Other means, such as a time-domain reflectometer (TDR) would then be employed to locate the fault.

The following series of equations gives us K, A, B and D:

$$A = K\cos\left(\frac{\theta_{SC} - \theta_{OC}}{2}\right)$$

$$B = K\sin\left(\frac{\theta_{SC} - \theta_{OC}}{2}\right)$$

$$D = \frac{2A}{1 + K^2}$$

Where: K is the magnitude portion of the impedance

$$K = \sqrt{\frac{Z_{SC}}{Z_{OC}}}$$

A is the real component of the impedance

B is the imaginary component of the impedance

Using the results of these calculations, the attenuation of the transmission line can be calculated using the following formula:

$$L = 5\log_{10}\left[\frac{1 + D}{1 - D}\right]$$

Where: L = Loss of the entire line in dB

The measured loss of the line is useful in determining if the line's actual loss is close to the rated loss as determined by the manufacturer. If the measured loss is very far from the manufacturer's rated loss for a given length and frequency, the measurements and calculations should be repeated. If the results are the same, there is likely to be a fault in the line.

To determine electrical length, the following formula should be used:

$$\beta l = \frac{\arctan G}{2}$$

$$G = \frac{2B}{1 - K^2}$$

Where: βl is the distance of the end of the transmission line, in electrical degrees, from the nearest quarter-wavelength at the frequency measured.

With a couple of simple bridge measurements and a pocket calculator, a great deal can be learned about a transmission line — probably enough to pronounce the line "good" or indicate a fault.

If a fault is indicated in a particular line, the next step is to obtain a TDR and locate the fault. The best case is where the fault is located very near one end or the other or in an area where the line is above ground. The worst is when the fault is in the middle of a buried line.

Once a fault is located, chances are the line can be repaired. The usual procedure is to cut out the damaged portion and splice in a new piece of line using splice kits obtained from the manufacturer. If the line is an older type no longer in production, a piece of a different type of line (as long as the characteristic impedance and size are the same) can be spliced in. Factory splice kits cannot be used to splice dissimilar line types, but EIA flange connectors can be installed and used to join the line pieces. The resulting mismatch will, in most cases, be so minor that it can be ignored.

Foam-dielectric lines that have gotten wet must be cut and spliced as discussed above. All of the water-soaked portion must be removed and replaced with dry line.

Wet air-dielectric lines can often be dried out once the source of the leak is located and repaired. The connectors are removed from both ends and a vacuum cleaner hose is connected to one end (usually the tower end) with electrical tape to form a tight seal. The vacuum cleaner is then turned on and allowed to run for several hours. This will usually pull all the water out of the line and evaporate any trace moisture remaining. The connectors are then reattached and the petcock at the tower end of the line opened. Dry air or nitrogen is then used to purge the line of the last vestiges of moisture. The petcock is then closed and the line pressurized.

4.6 Ground System Problem

Generally speaking, the only ground system problems that will show up on the antenna monitor, base current ammeter or at the common point are those very close to a tower base. Broken or missing radials, while detrimental to the overall efficiency of the array, seldom give any indication in the operating parameters of the array.

From time to time, however, grounding problems can occur which can cause significant headaches in the operation of an array. The worse the effect on the array operation, the closer the problem typically is to the tower base area. Frost heave can, over time, tear ground strap connections. An ATU with no solid ground connection will produce unpredictable and unstable array operation with the symptoms often appearing in places other than just at the tower where the problem exists. A ground screen that has lost its bond to the ATU/tower ground will produce an unstable driving point impedance at that tower, again affecting the entire array.

The key to most ground system related problems is instability. If the array characteristics change significantly from wet to dry, frozen to thawed, look for a broken ground connection.

Such problems are usually quite easy to correct once they have been located. Some heat, flux and silver solder will usually restore normal operation.

4.7 Tower Problems

Seldom do towers give problems that manifest themselves in the operating parameters of a directional array. They can, however, so they should not be discounted in the troubleshooting process if everything else has been ruled out.

The key to determining whether a particular tower has a problem is the measured self-impedance of the tower. The self-impedance is measured by disconnecting (“floating”) all the towers in the system and one at a time, using the bridge, oscillator and detector to measure the resistance and reactance of the towers right at the feed point at the base. If the towers are of equal height, type and cross-section, they should all exhibit very close to the same self-impedance. One tower at variance with all the others indicates a problem on the tower. In the case of dissimilar towers, the results of the self-impedance measurements should be compared to recorded self-impedance data. If that data is not available, it may be necessary to discuss the matter with a consulting engineer to determine if the measured self-impedance is close to the expected value.

If a tower is located with a self-impedance at variance with what is expected, lighting chokes, Austin transformers, isocouplers and the like should be suspected and checked first. Occasionally, tower section joints lose their electrical connection due to corrosion or loose hardware. Such joints on AM towers are usually tack-welded to insure good long-term connections, but such welds can break.

The easiest way to determine if tower sections are not making good electrical connection is to have someone shake the guy wires while the bridge is observed. If the impedance changes significantly when the tower is shaken, there may be a bad joint. An inspection of every joint on the tower will be required to isolate the problem.

5.0 Record Keeping

Perhaps the best tool in the troubleshooting and maintenance of a directional array is a good set of records. This starts with the field notes from the original array tune-up, if available, and notes on any subsequent adjustments, including notes on the reason for adjustments, repairs, etc. Such notes will contain invaluable information on impedances, component values, coil tap settings and turn counter readings.

It is advisable as well to make some static impedance measurements at each transmission line output of the phasor when everything is working properly. When a problem develops, simply repeating these measurements and comparing the results with the recorded values can provide a quick pointer to which transmission line, ATU or tower has the problem.

Jotting the tower self-impedance and driving point impedance values down on the wall or chassis of each ATU using an indelible marker is a good practice that can save a lot of time and trouble later on.

Marking each coil tap with a spot of paint is another practice that can pay off when there is a problem. The color of the paint used should be recorded in the notes along with the date it is applied. Later, if any adjustment is done, a different color paint should be applied to any coil taps that were moved and that information recorded. This practice will give you a good starting point should a coil clip become dislodged or an adjustment have to be made. The positions of the different paint spots on a coil can also reveal a trend over time.

Good record keeping requires discipline but sooner or later it will pay off. The conscientious engineer will take the time to make good notes on his activities, particularly as they concern a directional antenna.

5.0 Conclusion

There are many things that can go wrong with a directional array and there is usually a ready fix for each type of problem. Seldom, however, will cranking on the phasor repair a problem. This could result in chasing a bad antenna monitor or sample line or compensating for a component with a changing value. When antenna trouble comes, as in any troubleshooting situation, one should stop, think and search for the problem by conducting a thorough investigation and using logical thinking. The controls on the phasor should be used only to touch up array tuning after the problem has been diagnosed and fix adjust.

Other more complex schemes utilize phase quaderature compensation to achieve extremely wide bandwidth. This type of matching scheme is more typically used on master antennas fed by multiple co-located stations.

5.5 Deicing

Deicing equipment, either in the form of electric heat or radomes, tends to increase the complexity, cost, required maintenance and weight of an antenna. When ice forms on an antenna, the resonant frequency of the antenna tends to go down. A narrowband antenna with even a small amount of ice will present an unacceptably high VSWR to the transmitter, possibly leading to damage not only to the transmitter but also to the transmission line the antenna itself. Deicing equipment keeps ice from forming on the radiating elements, thus preventing this detuning. Broadband antennas, while detuned by ice just as more narrowband designs are, have sufficient bandwidth that the detuning has little effect on the load presented to the transmitter.

Keep in mind that high initial cost may be offset by many years of very low maintenance costs. The converse is also true. When selecting an antenna, the best approach is to select the very best antenna that your budget can stand. After all, what other part of your transmission system has more effect on the signal you present to your audience?

6.0 Transmission Line Types

In the case of FM antenna systems, there are generally two choices for transmission line types: rigid and semi-flexible.

Air-dielectric rigid line is, as its name implies, a fixed shape that is not intended to bend. It generally comes in 20-foot flanged or unflanged sections. Sections that are intended to go on the tower are generally equipped with factory-installed EIA flanges. Sections that are used for inside RF plumbing, such as between the transmitter, RF switch or patch panel, combiner and gas barrier are often supplied without flanges. Field flanges are available which are attached by silver-soldering or with hose clamps. A wide variety of adaptors, including reducers, elbows and 45-degree sections are available to allow routing of rigid transmission line to virtually any location within a transmitter building.

Semi-flexible line, aptly named because of its somewhat limited bending capability, comes in either air-dielectric or foam-dielectric types. In the case of air-dielectric line, the inner conductor is held in place with a Teflon spiral. With foam-dielectric semi-flexible line (available in sizes up to and including 2-1/4”), a foam dielectric material completely fills the space between the inner and outer conductors, holding a more-or-less constant spacing between the two. Semi-flexible line comes on a spool in a continuous run and is generally ordered to length. An EIA flange gas-barrier or gas-pass connector is ordered for either end to complete the transmission line run.

5.1 Pressurization

Either type of air-dielectric line requires a supply of nitrogen or dehydrated air to keep the line pressurized to a few p.s.i. above ambient. The purpose of the dry air is to keep out moisture. Pressurization of the line implies that the line must be airtight.

EIA flange connectors come equipped with rubber O-rings to provide an airtight flange-to-flange seal. Connectors fitted to semi-flexible air-dielectric line are equipped with special rubber seals that provide an airtight fit between the brass connector and the copper line.

A method of getting the pressurizing air or nitrogen into the transmission line must be provided, and this generally comes in the form of a gas-barrier. The gas-barrier can either be integral in a semi-flexible line connector or a stand-alone unit with an EIA flange on either end. A fitting is provided for connecting the pressurization tubing.

It is absolutely critical that moisture be kept out of air-dielectric transmission line. Moisture will cause oxidation in the copper, which increases attenuation at higher frequencies. Attenuation on the order of 4 dB per 100 feet has been measured in 3- and 3-1/8” semi-flexible and rigid air dielectric lines that have not been pressurized. This represents a tremendous power loss, which translates directly to signal loss.

5.2 Rigid vs. Semi-Flexible Line

There are advantages and disadvantages to both types of transmission lines. Rigid line has the advantage of lower losses. This usually amounts to a few hundredths of a dB per 100 feet over a comparable semi-flexible line. This can add up to a significant amount of power in the case of a long transmission line run.

Another advantage that rigid line has is that it is more repairable than semi-flexible. It can be removed from the tower in 20-foot sections, the inner conductor can be removed and both inner and outer can be cleaned. In the case of semi-flexible air-dielectric line, quite often a large section of the line must be removed and a replacement piece spliced in. The cutting process allows copper and Teflon shavings to fall into the line below the cut, and these shavings can accumulate in one location and produce an arc, causing further damage. Quite often, the only recourse in the case of a damaged semi-flexible line is to replace it in its entirety.

Semi-flexible line has the advantage of lower cost, sometimes as little as half the cost of a comparable rigid line. It also has the advantage of being in a continuous run as opposed to being joined with expansion connectors (“bullets”) every twenty feet. Expansion, contraction and vibration of a rigid line cause chafing where the expansion connectors join the inner conductors and this often eventually results in a less than optimal connection. The I^2R loss at the connection causes heat, which further degrades the connection and eventually produces a burnout.

7.0 Transmission Line Selection

A broadcast engineer designing an FM transmission system has a number of choices for transmission line size and type. The factors that enter into this decision are transmitter power, line length and antenna gain. All three factors are somewhat variable. It is not uncommon for a given ERP and antenna gain to have the transmitter power level determined by the transmission line size and type. Changing to a larger or lower-loss line may permit the use of a smaller transmitter, somewhat offsetting the added cost of the better line. The other side of that coin is that the larger line may require a beefier tower to support it, adding cost to the project. Usually, however, the choice is a little clearer.

7.1 Power Rating

The first step in finding a suitable transmission line for a system is to determine the approximate power the line will have to carry. This is calculated by dividing the effective radiated power (ERP) in kW by the antenna power gain, or by subtracting the antenna gain in dB from the ERP in dBk and converting back to kilowatts. This calculation will yield the antenna input power, or the transmitter power output less the line loss, which is as yet unknown. While the antenna input power does not represent the total power in the line, it is a good starting point. Keep in mind that in combined systems, the power in the line is the sum of the power of each station.

Next, go to the manufacturer's catalog and find a line that exceeds the calculated line output power by a good margin, keeping in mind that the input power (which is the maximum power the line will have to carry) will be somewhat higher. While any of a number of transmission lines may have an adequate power rating, there will be few choices that offer both acceptable performance and economy. A good rule to follow when selecting a transmission line is to use the smallest line possible consistent with the required power handling capability. There are certainly exceptions, such as in the case of a very long transmission line, where it may be more important to keep losses (and thus long-term operating costs) down than the initial investment. As a rule, however, the goal should be to insure adequate performance while minimizing cost.

7.2 Line Loss

With a likely candidate selected, find the loss of the line at the operating frequency and line length. Manufacturers typically provide this information in dB per 100 feet or 100 meters. Divide the line length in feet or meters by 100 and multiply by the per unit loss to get the total line loss in dB.

7.3 System Calculation

To find the transmission line input power (or transmitter power output, TPO), add the line loss in dB to the antenna input power in dBk. Convert back to kilowatts by dividing by ten and taking the antilog. The loss of the line in kilowatts can be determined by subtracting the antenna input power from the transmitter power output. Divide the antenna input power by the TPO and multiply by 100 to calculate the efficiency of the line in percent.

Table 1 below shows an example of a system calculation. The system specifies an ERP of 50 kW, a four-bay antenna, and 500 feet of line at 100 MHz.

Table 1

ERP	50.00 kW	16.99 dBk
Antenna Gain	2.133	3.290 dB
Antenna Input Power	23.44 kW	13.70 dBk
Line Loss	0.851	0.700 dB
Transmitter Power Output	27.54 kW	13.40 dBk

Rounding in accordance with 47 C.F.R. §73.212, the *operating* TPO becomes

27.5 kW.

7.4 Safety Factors

The next question becomes one of headroom. Is a 3-inch line with a 42 kW power rating adequate? To find the answer, we must *derate* the line for VSWR. To do this, simply divide the power rating of the line by the worst-case VSWR. A good number to use to account for possible icing of the antenna is 2:1. In our example, the derated average power capability of the line for 2:1 VSWR is 21 kW. Is this reasonable for a 27.5 kW input power?

The answer to that question is determined by estimating the risk of the VSWR ever getting to that point. Are the protective circuits in the transmitter reliable? Are there deicers or radomes on the antenna, and are they effective and reliable? In most cases, you can count on your protective and deicing systems to do the job.

It is not wise, however, to put your eggs all in one basket. An outboard VSWR or reflected power monitoring device is a good investment to protect your very expensive transmission line. The trip point of the device should be set below the level that would exceed the rated average power of the line with full transmitter power output. In our example, the line is rated at 42 kW. Divide that by the TPO of 27.5 kW to find the maximum VSWR that will derate the transmission line to the TPO. In our example, this VSWR is 1.53:1. The idea is to make sure that in the worst case — with the transmitter running at full power and some sort of antenna problem — the line will be protected.

8.0 Transmission Line Installation

Little thought is given to proper transmission line installation in many cases. A bag of cable ties or a box of Wraplock in the tower rigger's pouch is deemed sufficient to secure the line to the tower. Most radio engineers have seen transmission line installations where little more than electrical tape or cable ties was used to secure the line.

While such inexpensive measures will work in the short term, over a period of time, trouble will likely come as a result. Cable ties deteriorate with exposure to sunlight and extreme temperatures, becoming brittle, breaking and falling off. Thermal expansion/contraction as well as other differential motion between tower and line can cause Wraplock to chafe against the outer jacket, often resulting in the outer jacket and eventually the outer conductor being cut through. Once this happens the inside of the line is exposed to the elements.

8.1 Installation Hardware

Transmission line manufacturers offer a wide array of mounting hangers, brackets and hardware that are designed to protect lines from differential motion problems and keep them working properly for many years. In addition to the hardware, line manufacturers publish specifications for mounting hardware, including recommended spacing between hangers for different wind load and radial ice values. The published values are not simply theoretical numbers or designed to promote the sale of hardware. They have been derived from extensive empirical data — including wind tunnel testing — and are based on the EIA RS-222 standard (Structural Standards for Steel Antenna Towers and Antenna Supporting Structures).

8.2 Environmental Factors

Where a tower is located has an impact on the installation of a transmission line on the tower. Values of *design basic wind speed*, the maximum wind speed at a height of 10 meters over open terrain, are published for counties and states in EIA TIA-222-E. This is a good place to start when considering what hardware to use in a particular installation.

The maximum amount of radial ice accumulation is another factor that must be carefully considered when designing a transmission line installation. Some locations, particularly those in the southern tier of states, are especially prone to ice storms and large accumulations of ice on tower structures and attachments. Warm, moisture-laden air rides up and over cold surface air and falls as rain. When the supercooled raindrops impact the surface and objects on the surface, they instantly freeze. It is not uncommon to have 1" or more of radial ice build up on a tower structure, its antennas and lines in such circumstances, greatly increasing the dead weight and cross-section (and thus wind loading) of the tower, antennas and lines.

With the design basic wind speed and maximum expected amount of radial ice in hand, the manufacturer's installation charts can be consulted to determine the type of hanger which should be used and the recommended maximum hanger spacing for a particular line. The quantity of hangers can then be calculated.

8.3 Installation Methods

The next step is to determine how the hangers will be attached to the tower structure. Many towers provide mounting tabs to which hangers can be directly bolted. This is the simplest means of attachment, and provides for very secure mounting.

Another means of mounting utilizes hose clamps or some other means of leg attachment. The hose clamp, sometimes called a "round member adapter," clamps to the tower leg and to the hanger itself through a slot in the hanger. When utilizing this attachment method, especially with larger diameter transmission lines, some means must be provided to get around the flanges where tower sections mate. Specially made standoff kits are available from line manufacturers to provide a means of getting the line securely past flanges without allowing the line to chafe against the flanges.

Hoisting grips are "Chinese handcuff" devices that are designed to securely attach to a transmission line and pull it up the tower without stretching or distorting the line. Typically, one hoisting grip should be used every 200 feet to spread out the load. This helps keep the weight of the line on the load line and off the line itself. Once the line is in place on the tower, the hoisting grips are secured to the tower to provide permanent vertical support.

8.4 Grounding

It is very important to "ground" a transmission line to the tower at both top and bottom and in some cases at several locations along the line's length. When lightning hits the tower, high-level currents will flow down the tower in all the available parallel paths, including in the outer conductors of transmission lines. Because copper has a lower DC resistance than the steel of the tower, greater currents are prone to flow in the transmission line outer conductors than in the tower steel. This will often result in significant potential developed between the transmission line outer conductor and the tower itself, resulting in arc-through of the transmission line outer jacket and pitting of the transmission line outer conductor. In extreme cases, the pitting will actually penetrate the outer conductor, opening the line to the elements and eventually destroying the line. Grounding or "bonding" the transmission line to the tower at frequent intervals is a good means of keeping the potential between the line and tower low and preventing such damage.

8.5 AM Tower Installation

AM towers are a special case. Depending on the feed system, there are several methods of installing a transmission line on an AM tower. In grounded-base (skirted or shunt-fed) towers, the method is essentially the same as with any other tower, except that more frequent bonding of the line to the tower should be done to minimize RF arcs through the line jacket.

There are two basic means of installing transmission lines on insulated-base AM towers. If an isocoupler or isocoil is used, installation above the base insulator is the same as for a grounded-base tower. If a quarter-wave stub is used, the line is installed using insulated hangers. In that case, the line is not bonded to the tower at any location below the shorting stub.

8.6 Rigid Line Installation

Rigid transmission lines are another special case. Rigid lines are fixed to the tower at the top of the run and mounted in spring hangers for the remainder of the vertical run. A nylon-jacketed collar is provided on each spring hanger to prevent horizontal motion. A spring connects the collar to a clamp that is affixed to the line below the collar. The manufacturer provides recommended settings for the springs to insure that the correct amount of tension is applied to the line at each location. The purpose of the springs is to allow differential motion between the line and tower structure because of thermal expansion. A rigid copper transmission line exhibits considerably more thermal expansion than a steel tower. If this is not allowed for, the line will buckle.

9.0 Maintenance

In most cases, once a transmission line and antenna have been installed on a tower, little thought is given them until something goes wrong. That is unfortunate, because they do require a certain amount of maintenance to keep them reliable and operating at peak efficiency.

9.1 Visual Inspections

Regular mechanical maintenance of an FM antenna system should include a complete visual inspection at least annually. This can be done in conjunction with relamping or other tower maintenance to minimize costs. Excitation must be removed from the antenna and other steps taken to insure that the tower is safe for workers to climb and work in the vicinity of the antenna.

The tower worker making the visual inspection should look at each element in the array for proper installation; for burns or pitting on the element ends; for cracks, carbon traces or defects in insulators; and for any evidence of abnormal mechanical stresses. Weep holes in the antenna elements, if any, must be oriented so that they face down.

9.2 Deicer Maintenance

If the antenna is equipped with deicers, they should be turned on during the inspection. The tower worker should then verify that the deicer in each element is working by feeling of the element.

One of the most dangerous icing situations for an FM antenna occurs when all the elements' deicers are working except one. All of the elements except that one remain clear of ice, and a serious mismatch occurs in the interbay line. Because the mismatch is limited to that one element, the transmitter's VSWR foldback circuit may not see sufficient reflected power to cause it to activate. With full power being fed to the antenna, an arc can occur and sustain itself until serious damage has been done to the antenna. From a protection standpoint, it is better to operate with no deicers than with a partially operating system.

A good deicer maintenance tool is a permanently-installed AC ammeter on the deicer circuit. With the deicers operating normally (and after a ten-minute warm-up period), mark on the meter face the nominal current. From time to time, the deicers should be turned on and allowed to warm up. The current can then be checked against the mark. If there is a deviation, a tower worker should be dispatched to investigate.

9.3 Transmission Line Inspection

Transmission lines should likewise be visually inspected annually. The connections at the top and bottom should be inspected for security, and any evidence of movement should be investigated. Ground connections should be checked and tightened and any corrosion should be removed.

In the case of rigid transmission lines, the length of each hanger spring should be checked against the manufacturer's recommendation. If necessary, the springs should be adjusted. Nylon buttons or bushings in the spring hanger collars should be checked. Should these fall out or become damaged, the copper transmission line will chafe against the metal of the hanger. This will eventually wear through the copper of the line, leading to line failure.

Rigid and semi-flexible lines should be checked for "hot spots" near flanges and connectors. In the case of rigid lines, this is every twenty feet. An infrared thermometer can be used for this, or the tower worker can simply feel of the joint and compare it to the adjacent portions of the line. Localized discoloration in rigid lines is a good indicator of abnormal heating. The cause of any significant heating should be investigated, as heating at a joint is a precursor to a line failure. Such heating is often caused by a "split bullet" or chafing in the inner conductor where it makes contact with the "bullet." The heating is evidence of I^2R loss in the joint, which is power not being radiated. In many cases, heating in the joints can quickly produce a thermal runaway situation leading to catastrophic failure of the line.

One tool available today that is of great help in locating hot spots in a transmission line or antenna is infrared photography. Hot spots will show up as a lighter color. The advantages of this method are that it can be done from the ground and it can detect subtler temperature rises. While IR photography has several advantages, it is not a substitute for a good visual inspection.

9.4 FM on AM Inspection

In some situations where an FM antenna is mounted on an AM tower, the transmission line will be mounted using insulated hangers. Each insulator should be inspected for cracks and carbon traces. The shorting stub, usually located somewhere close to 90 electrical degrees (at the AM frequency) above the tower base, should be checked for a good electrical connection at the line and the tower.

Other FM on AM situations employ an isocoupler to cross the base insulator with the FM transmission line. In these cases, it is important that the transmission line be electrically bonded to the tower frequently along its length. Each bond should be checked for good electrical connection. In addition, the entire outer jacket of should be checked for evidence of arc-through to the tower. If such evidence is present, it likely indicates that more frequent bonding is needed. Such arc-through, if permitted to continue, can eventually penetrate the outer conductor of the line and open the line to the elements.

Grounded-base AM towers, such as folded unipoles and shunt-fed antennas, likewise require the FM transmission line to be frequently bonded to the tower steel along its length. The same checks of the bonding and outer jacket should be made on grounded-base AM towers.

9.5 Pressurization Maintenance

Proper pressurization of air-dielectric lines is critical to their performance. Pressurization with dry air or nitrogen has a direct effect on the breakdown voltage (and thus the power handling capability) of the line. If moisture is allowed to enter the line, corrosion will result, producing higher losses, hot-spots and eventual line failure. The pressure integrity of the line and antenna should be checked by closing the air valve feeding the line at the bottom of the run and observing the line pressure over a period of several hours. If the pressure bleeds off, there is a leak and it should be located and repaired.

An adequate nitrogen supply should be maintained at the site to insure that the supply is not exhausted before another delivery can be made. If the pressure integrity of the line is maintained, very little nitrogen should be used. Pressurization equipment should be regularly inspected, at least weekly, and maintained in good working order. Desiccant should be rotated out and dried or replaced whenever it begins to turn from blue to pink. A dehydrator with a saturated desiccant pumping moist air into a line is almost as bad as having no pressurization at all. The use of a self-recharging dehydrator will prevent this from ever happening.

9.6 System VSWR Monitoring

Finally, a check of the system reflected power should be made during every site visit. A significant change, up or down from the nominal value, should be investigated. A more sensitive indicator of load impedance in some power amplifier designs is the screen current. Higher screen current generally indicates a lighter (higher Z) load. If PA tuning is otherwise correct, an increase in screen current may be an indicator of a developing antenna or line problem.

In addition to checking the reflected power, the VSWR foldback and trip circuits in the transmitter or external protection device should be checked from time to time to insure that they are working. Transmitter manufacturers usually provide a procedure for checking and adjusting the internal protective circuits.

If the directional coupler(s) use removable slugs to detect forward and reflected power, they should be checked regularly for proper operation and good connections. A reflected power meter that reads zero all the time may be an indication that the connection, either between the slug and the coupler or between the coupler and the transmitter, is bad. If that is the case, chances are there is no VSWR protection in place, which can lead to a catastrophic failure of the line/antenna and damage to the transmitter.