Review and Analysis of Medium Wave Directional Antenna Sample Systems

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Abstract — The use of method of moments techniques has resulted in changes of some of the conventional thinking for medium wave directional antenna sample systems - that is the instrumentation for monitoring antenna system parameters. Sample loops on the antenna structures and toroidal current transformers in the feed systems have long been used to monitor directional medium wave antenna systems. This paper will reexamine the historical practices and provide analysis of current thinking on best practices for these types of sample systems.

Index Terms — Amplitude modulation, Antenna arrays, Antenna measurements, Medium Wave, Sample Systems, Antenna theory,

I. INTRODUCTION

THIS paper is intended to compile in one document an analysis of the historical practices and current thinking on best practices for these types of Medium Wave (MW) directional antenna sample systems. We will examine all of the current methods used for sample systems and provide analysis of these systems with recommendations of which method is ideal for each application.

The art of MW antennas is a mature area of radio engineering. There have been numerous works on this subject and we acknowledge the work of our predecessors. After more than 80 years, there is still much work being done in this field. Changing regulations, demands of land use regulations, and coverage requirements that have changed due to shifting population densities have continued to require MW facilities to be combined on the same antenna system with the systems optimized to provide the radio station with the best facility in terms of population covered and density of signal in desired coverage areas. The vast majority of MW directional antennas have historically been implemented in North America, for both interference protection and coverage maximization. We are also seeing an increase in implementation of MW directional antennas outside of North America for optimization of coverage and interference prevention features.

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II. REVIEW OF DIRECTIONAL ANTENNA BASICS

Directional MW antennas in ITU Region II are defined (for the simple case – simple vertical radiators without top loading and without sectionalized antenna elements) by the following nomenclature:

Tower Number	Field	Phase	Spacing Distance	Bearing	Height

Tower Number – Each element of the array is given a unique number.

Field - A ratio of the far field contribution from this element related to the reference element. This is expressed as a ratio - *(F_i)*.

Phase – The phase of this element related to the reference element. This is expressed in electrical degrees (1 wavelength = 360 degrees) - *(y_i)*.

Spacing Distance – The physical distance between elements. This term is expressed in electrical degrees – *(S_i)*.

Bearing – The direction of one element from the other. This direction is expressed in a geographical system in degrees referenced to True North where North is 0°, East is 90°, South is 180° and West is 270° - *(f_i)*.

Height – The element height is expressed in electrical degrees - *(G)*.

The general form of the equation to calculate a directional antenna pattern for a given azimuth *(f)* and elevation *(?)* (where the elevation angle 0° is the horizontal plane and 90° is the vertical or zenith) is:

$$E(j,q)_{th} = \left| K\sum_{i=l}^{n} F_i f_i(q)\angle\left[y_i + S_i \cos q_i \cos(j_i - j)\right] \right|$$

$f_i(q)$ is the vertical plane distribution factor expressed by the following equation:

$$f_i(q) = \frac{\cos(G \sin(q) - \cos G)}{(1 - \cos G)\cos(q)}$$

Where n is the number of elements in the array incremented by i, f is the azimuthal angle, f_i is the orientation of the i^{th} element from the reference element, ? is the elevation angle, and K is the multiplying constant that determines the pattern size in units of mV/m. See [9] for a more complete discussion of this subject. This constant is the no-loss multiplying constant expressed as:

$$K = \frac{E_s \sqrt{P}}{rms_h}$$

Where E_s is the horizontal radiation for the hemispherical radiator expressed in mV/m at 1 km, P is the input power (rms), and rms_h is the root-mean-squared effective field intensity over the hemisphere. The derivation of E_s is:

$$E_s = \left(\sqrt{\frac{P_r R_c}{2p \cdot r^2}}\right)\left(10^3 mV/m\right)$$

Where P_r is the radiated power in Watts, R_c is the impedance of free space (120p), and r is the distance from the antenna in meters.

The RMS of the antenna pattern is the Root-Mean-Square (RMS) electric field strength of the antenna pattern in mV/m at 1 km.

The RSS of the pattern is the Root-Sum-Square (RSS) of the inverse distance field (in mV/m at 1 km) of each of the elements for the array (for the power delivered to that element as it operates in the array) in the horizontal plane. This is expressed mathematically:

$$E_{RSS} = K_{loss} \sqrt{\sum_{i=1}^{n} F_i^2}$$

Where K_{loss} is the power loss for the array. This is typically assumed to be a 1 ohm loss in power and calculated by the I^2R based on the antenna current and impedance. See [9] for a more complete discussion of this subject.

A figure of merit in directional antenna design is the RMS/RSS ratio. For ease of tuning, stability, and system bandwidth it is best if this figure is less than 2:1. A ratio of 1:1 or less is considered to be very desirable.

The field produced by any one element is directly proportional to the current flowing in the element as shown by:

$$E = K \int_L I(s)ds$$

Where K is the multiplying constant that determines the pattern size, I is the current in the element, and L is the length of the vertical radiator.

These equations are used for the regulatory process and are simplifications of the actual electromagnetic physics involved in producing a directional antenna; however, these are good approximations and are sufficient for the allocation process and any discussions of propagation and coverage. The primary shortfall of these equations is that they assume sinusoidal current distribution, which is also a good approximation but has some shortcomings in the calculations of currents and impedances in the base region of the antenna system.

Historically, MW directional antenna performance monitoring was determined by comparing the current that flows into or on the antenna elements (antenna sample system) along with field strength measurements in the far field. In the US, the FCC is (at the time of this writing)considering allowing the move to a better defined antenna model with a better defined sample system, and not requiring far field strength measurements to verify the performance of the system.

Sample systems obtain a sample current from each antenna element and compare the ratio and phase to the sample from the reference element. There are antenna monitors approved by FCC manufactured by Potomac Instruments and Gorman Redlich for this purpose. These conditions can also be determined by the use of a network analyzer [15].

An important distinction should be made between the antenna monitor reading and the field parameters (the field ratio is the ratio of far field contribution from this element related to the reference element). The antenna monitor readings are the ratio and phase of each antenna element from the sample system that are displayed on the antenna monitor. These two sets of parameters often are quite different from each other depending on the type of sample system. It is not uncommon for these parameters to be confused and to have a system misadjusted to display the field parameters on the antenna monitor. The regulatory authorities in some countries actually normally require this.

We believe that careful modeling and system tune-up provide an antenna system that is in better compliance with the underlying antenna specifications that are derived from the allocation process.

III. Choice of Sample Systems

The choice of sample system has not always been the same over the past 60 years. The factors that should be considered are: regulatory requirements; system capital and maintenance costs; suitability for the characteristics of the array; system reliability; ease of tune-up; environmental conditions; and designer preferences. All of these factors should be weighed to select an appropriate sample system.

In the US, the FCC has specific requirements for sample systems. A short list of some of these requirements (as of September 2008) is:

- An antenna monitor that meets the requirements of 47CFR§73.53 *Requirements for authorization of antenna monitors*
- Equal length coaxial transmission lines with solid

- outer conductor and foam polyethylene dielectric or low change in electrical length with changing temperature for unequal length lines
- Tower mounted sample loop or toroidal current transform (TCT) coupling element

The choice between a tower mounted sample loop and a toroidal current transformer should be based on the appropriateness for the array. There has been a consensus in the industry that tower base sampling using TCTs should not be used for systems that have antenna elements that are between 120° and 190° in height.

The use of sample loops may remove some ambiguity of the antenna modeling for the system tune-up and are preferred in some systems for this reason. For systems that are in areas that are prone to high winds or icing conditions, tower-mounted sample loops may not be appropriate due to susceptibility to damage.

Over a six year period from 1969 to 1976, the FCC, through two separate Rulemaking Proceedings, developed technical requirements for sampling systems for AM broadcast stations employing directional antenna systems. Prior to that time there were no standards for sampling systems. In Docket 18471 [37], the FCC adopted Rules specifying technical requirements for type approval of antenna monitors. The comments filed in this proceeding demonstrated a need for the FCC to develop similar technical standards for sampling systems. In a subsequent Rulemaking proceeding (Docket 19692) [38], the FCC adopted rules specifying technical standards for sampling elements and the transmission lines that connect the sampling elements to the antenna monitor. The new Rules allowed for only two types of sampling elements to be used: single turn, rigid, unshielded, loops to be mounted directly onto each tower at a fixed orientation; and, for towers less than 110 electrical degrees in height, adequately shielded current transformers to be mounted at the antenna feed line location.

The sampling system Rules were further modified in 1985 with the issuance and subsequent adoption of Rules in Docket MM No. 85-90 [36]. In this Proceeding, the sampling system Rules were modified to reflect performance standards in terms of accuracy and stability rather than upon construction specifications. As an outgrowth of this proceeding, the technical criteria and procedures for obtaining approval of a sampling system were clarified and expanded by the FCC's issuance, in December 1985, of a Public Notice entitled, "Criteria for the Approval of Sample Systems for Directional AM Broadcast Stations. The criteria contained in the 1985 Public Notice remain in force today [18].

The 1985 Public Notice again describes only two types of sampling elements; rigid tower mounted loops and shielded current transformers. The FCC's Rules however do have general provision that allows for the use of other sampling system configurations.

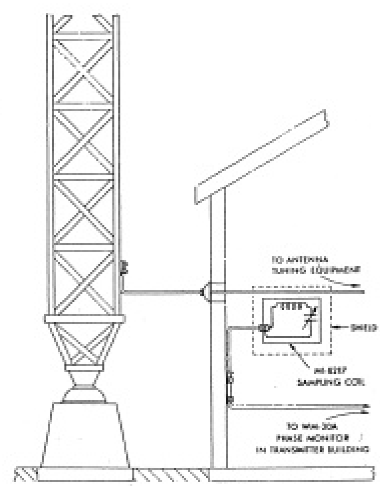
IV. Sample Loops

A. History

Sample loops have been used on directional antenna systems from the early days of AM radio dating back to the late 1930s. Before this time, when the first directional stations in the United States were licensed, no methods for monitoring antenna current phase were available. At that time, only the current amplitude was monitored using thermo-couple ammeters. Subsequently, a few directional stations, like WSUN in St. Petersburg, Florida, were licensed in the early 1930s not requiring the phase of the current for each tower be monitored.

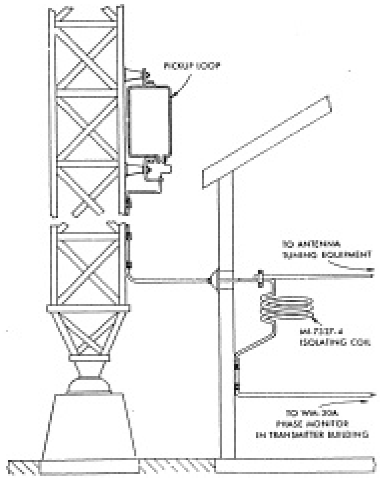
During the mid 1930s, the first phase monitoring system was developed and produced. Initially, the current phase was detected using a magnetically coupled pick-up located in the antenna tuning unit. RCA was one the first manufacturers of such a device using the MI-8217 Sampling Coil as shown in Figure 1.

Fig. 1



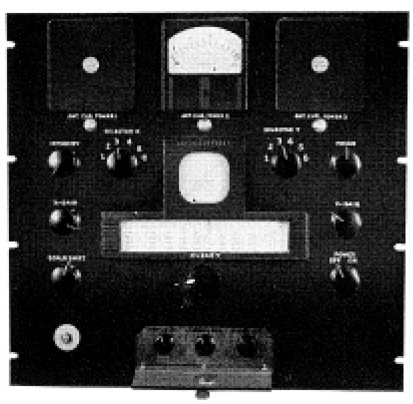
It was only a short time later when the first "pickup loop" was introduced. A single turn coil of an appropriate size as to induce a sufficient voltage to drive the phase monitor was mounted on one of the legs of the tower as shown on Figure 2.

Fig. 2



With either of the aforementioned sampling systems, RCA supplied a phase monitor WM-30A as shown in Fig. 3. Western Electric and Andrew also made phase monitors.

Fig. 3



In 1937, John Morrison of Bell Telephone Laboratories submitted an article to the Proceedings of the IRE suggesting a simple method for observing current amplitude and phase relations in antenna arrays. The article shows a two-element antenna array at station WEAN in Providence, Rhode Island, supporting angle-iron single-turn pickup loops at each tower. This equipment was reported to be first used in November 1936.

During the next 30 years, through the 1950s and 1960s, technology regarding the sample loop remained static, but development of the monitors continued with the introduction of the Models 108E and PM112, both produced by Nems-Clark, a division of Vitro Corporation. The E. F. Johnson Company was also a major supplier of sampling systems as well as phasing and coupling equipment during this time period.

It wasn't until the early 1970s that the Federal Communications Commission issued a new rule-making regarding sampling systems and monitors requiring type approved equipment. This act made obsolete all existing monitoring systems. A major change in the requirements was that the pickup devices be non-adjustable. Toroidal current transformers became acceptable devices to use for measuring base currents and providing current samples for the antenna monitor and sample loops had to be non-rotatable. The new rules required single turn, unshielded, fixed sample loops or toroidal current sensors to monitor antenna current magnitude and phase. At this point in time, a newly formed company, Potomac Instruments, anticipated the coming changes and was the first to bring to the market the type accepted and popular AM-19 and subsequently followed with the AM-1900 series digital antenna monitors 25 years later. Other manufacturers of modern antenna monitors have included Delta Electronics and Gorman-Redlich. Antenna monitors that measure both the ratios and phases of tower currents electronically replaced the separate phase monitors and remote current meters that had been used in the past.

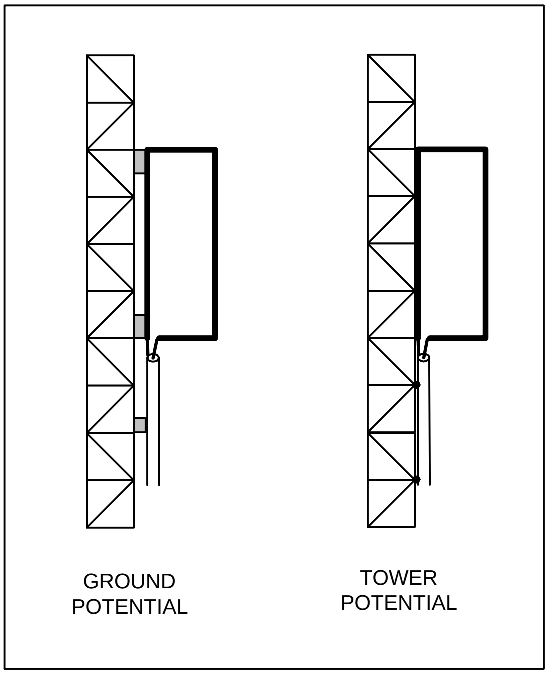
B. Best Practices

The sample loop is still commonly used today, especially in cases when towers are significantly over 1/4 of a wavelength tall. It is in the form of a rectangular loop of conducting material, such as aluminum or steel angle or copper pipe, mounted on the side of the tower at a height near one third of the height of the tower [26]. The height of the loop should be at least three meters above ground level so as to avoid the possible effects of strong displacement currents, which may exist very near each tower base. The dimensions of a loop can vary from one to two meters on a side depending on the amount of induced voltage required to drive the antenna monitor.

It has been noted that if sample loops are located at the height where the current in the element would be at a minimum if the tower were detuned in the horizontal plane as determined by the moment method model, the antenna monitor reading (ratio and phase) will be the same as the field parameters for each element in an array of physically identical antenna elements [35]. This requires careful modeling that is calibrated with antenna system measurements. This location is typically very close to 1/3 of the height for towers that are between 60° and 190°.

The sample loop is normally mounted on one leg of the tower as shown in Figure 4. Either ground potential or tower potential mounting configurations have been used. A ground potential loop was used in the early days before toroidal sample systems were available. These loops were mounted within three meters of the base insulator for electrically short towers. Until the last 10 years, most sample loops were placed at tower potential for electrically tall towers and at a current maxima further up the tower with toroidal sample systems reserved for shorter tower applications.

Fig. 4



The sample line is connected to the loop via a weatherized connector and proceeds down the tower, being bonded to or insulated from the tower at several points depending on the chosen mounting configuration. If the sample line is bonded to the tower, it must be wound into an isolation coil at the tower base or insulated from the tower for approximately one-quarter wavelength above ground level to present a large reactance as not to severely effect the drive impedance of the tower. The isolation coil will usually consist of enough turns to produce 100-150 µH of inductance and sometimes will have a parallel capacitor that may be adjusted for antiresonance. From the grounded side of the isolation coil, the sample line will proceed to the antenna monitor, usually directly buried with the transmission line and power cables coming from the transmitter building.

Often times the sample lines are of equal length in order to simplify the calculations required for the expected antenna monitor readings. If the lines are not of equal length, it will be necessary to determine the attenuation and phase delay differences between the lines to each tower. The sample lines are typically phase-stabilized coaxial cables constructed of a copper-clad aluminum center conductor, low-loss cellular polyethylene foam dielectric, and a solid corrugated copper outer conductor.

Loop construction should be:

- Oriented such that the outer edge to the loop is equidistant from the adjacent legs of the tower
- Rigidly mounted in an identical manner on each tower
- Bonded to the tower at the connector end only
- If “grounding kits” are employed on the transmission line, the one nearest to the sample loop should be installed as close to the RF connector as possible to avoid forming a secondary loop. Additional grounding kits should installed at intervals of no more that 30° and at the base (In high power systems with very small loops, the loop should be insulated with the ground provided on the sample line as close as possible to the loop to avoid the secondary loop problem)
- Dissimilar metals should be avoided to prevent galvanic corrosion
- Electrical connections should be weatherproof

The problem of determining the voltage at the terminals of a sample loop is shown in the following equation, which assumes a simplified formula neglecting finite dimensions of loop material, size of tower leg, voltage induced by electrostatic coupling, and internal impedance of sample loop.

$$V/A = (F)(L)(K)$$

F is frequency (Hertz).
L is loop length (feet).
K is a constant based on loop and tower geometry.

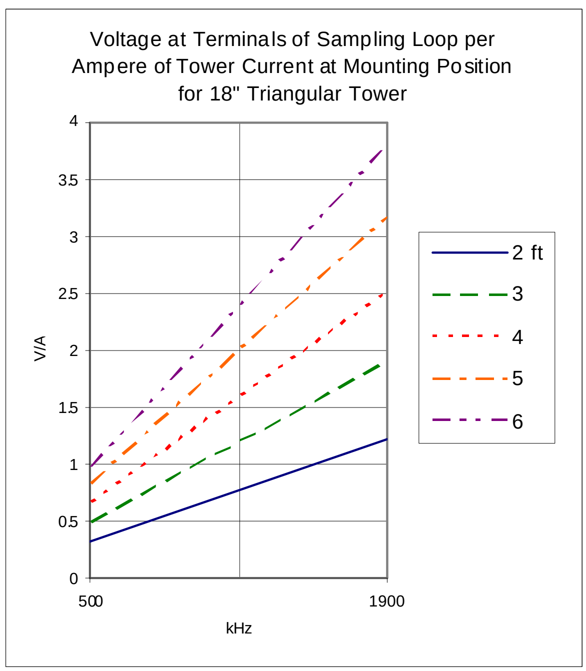
For a triangular tower with loop-to-tower leg spacing of four inches and a loop width of 18 inches:

Table I

Tower Leg Spacing(inches)	K
18	3.33×10^{-7}
24	3.03×10^{-7}
36	2.73×10^{-7}

Fig. 5 shows a graph predicting the induced voltage of a loop given five loop lengths using an 18-inch triangular tower.

Fig. 5



C. Example Case

A recent project utilizing sample loops was a particular challenge as it involved a diplexed directional array with varied tower heights. A total of six towers were used with two differing heights, one type being top-loaded. Given the two frequencies and two tower heights, it was necessary to decide if a single loop could be shared by each frequency and what height would be appropriate to mount each loop. Twenty years ago, this would have been a difficult problem to solve but with the advent of computers, coupled with moment method numerical modeling software, a solution is readily available.

The loop heights were chosen between 33 and 40% from the base of the tower height. The results of the computer model gave the predicted amplitude and phase of the current at that point for each frequency in order to produce the required patterns. Table II shows a table of the predicted input voltages for diplexed operation.

Table II

	Station A		Station B	
Tower	Day (V)	Night (V)	Day (V)	Night (V)
1	13.3	7.1	--	4.4
2	13.3	7.2	17.8	10.2
3	8.1	5.1	--	9.5
4	12.6	6.1	7.4	3.6
5	7.2	0.8	7.0	--
6	9.4	1.2	21.1	--

In order for a single loop to be used for both frequencies, it is required that the input voltages meet the specifications of the antenna monitor. As can be seen from the table, all range values fall within the specified input level range of the Potomac Instruments 1901 monitor (0.3 V to 25 V RMS carrier). As a result, it is possible to use a single loop for each tower to service both frequencies. Filters are required at the inputs to the monitors so that each reads the sample data at the correct frequency.

V. Toroidal Current Transformers

A. *History*

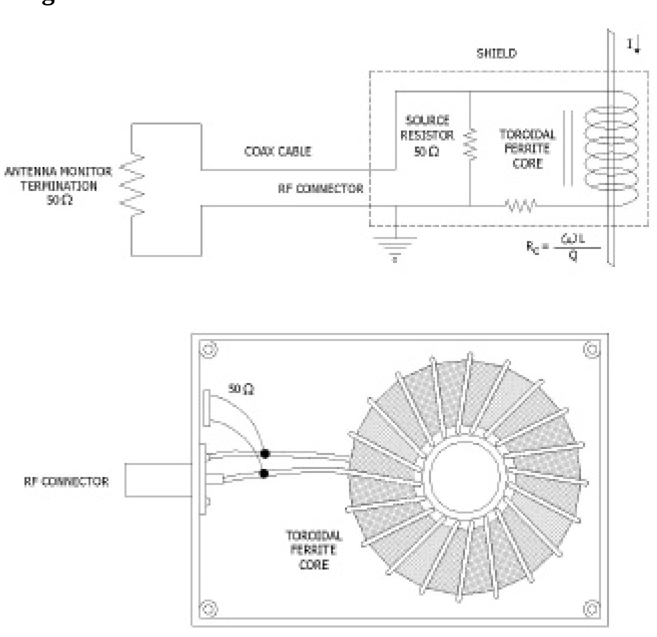
The use of Toroidal Current Transformers (TCT's) for sampling the relative magnitude and phase of feed line currents in directional antenna systems did not see widespread use until the early 1970's when Delta Electronics Inc. ("Delta") introduced its TCT series of toroidal current transformers. In a paper delivered in October, 1974, at the National Association of Broadcasters' Directional Antenna Seminar, Charles S. Wright, then Vice President of Engineering for Delta, stated that approximately 200 TCT-1 transformers had been delivered. Considering an average of three TCT per directional antenna system this corresponds to only about 67 stations, a small percentage of the total number directional stations authorized in 1974. Today the use of TCT-based sampling systems far exceeds the use of sampling systems employing tower mounted loops.

The basic design of the TCT sampling element has remained largely unchanged since the early 1970's. A Delta Model TCT-1 toroidal current transformer is shown mounted within an Antenna Tuning Unit cabinet at the base of a directional antenna in Figure 6. The feed line connecting the output of the tuning network to the base of the tower passes through a teflon lined pass hole in the center of the unit. The case of the TCT is grounded by directly mounting the unit on a four-inch ground strap. The grounded case provides an excellent shield that attenuates undesired stray fields from nearby tuning unit components, preventing current from being induced onto the toroidal windings of the transformer. In this configuration the feed line to the tower is the primary of the transformer and toroidal windings on a ferrite core within the TCT form the secondary of the transformer.

A simplified schematic diagram of the Delta TCT-1 current transformer is shown in Figure 7 [34]. The output voltage delivered to the antenna monitor is a function of the TCT source resistance, the antenna monitor terminating resistance and the number of windings. Transfer resistance for typical TCT's manufactured for AM broadcast use range from 0.25 to 1 Ohm, corresponding to an output voltage to current ratio of 0.25 to 1.

Fig. 6

Fig 7.



B. Best Practices

The primary characteristics that make the TCT an attractive choice as a sampling element include: low installation and maintenance cost, stability, accuracy and accessibility. In addition, these units are typically mounted within a tuning house or outdoor tuning cabinet such that they are not exposed to harsh environmental conditions. The main issue with the use of TCT's as sampling elements is associated with the sampling location. As was stated above, sampling the current on the antenna at a location corresponding to approximately one third of the height provides the best approximation of the relative field radiated by the antenna. Since the TCT is installed on the feed line at the base of the antenna, the sampled current at this location does not directly correspond to the radiated field.

Moment method modeling studies performed by Rackley and Folkert [33] on a three-tower directional antenna system demonstrated that for towers having heights of less than approximately 120 degrees or greater than 190 degrees, base current samples provide a reasonable approximation of the relative magnitude and phase of the radiated field. The graphs of Figures 8 through 11 [33] compare the relative magnitudes (ratios) and phases of the base current, base voltage and radiated field (Ref) for tower heights of 90 and 165 electrical degrees.

For the 90 degree tower height case, the relative base current magnitude and phase maintain the same approximate slope as the relative radiated field magnitude and phase over the study range although the absolute value differs due to the suboptimal sampling location. In the 165 degree tower height case, the slopes of both the relative base current magnitude and phase differ substantially from those of the relative field and the relative phase differs markedly in absolute value. For this reason, base current sampling is not recommended for tower heights between 120 and 190 degrees.

Fig. 8

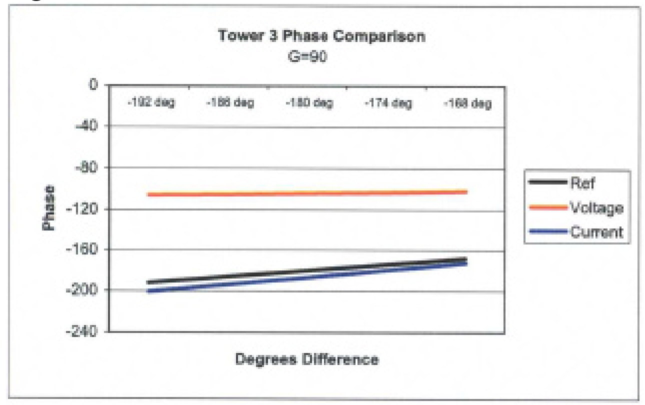


Fig. 9

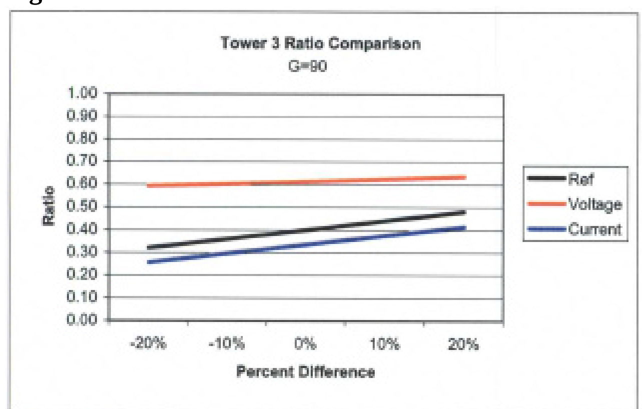


Fig. 10

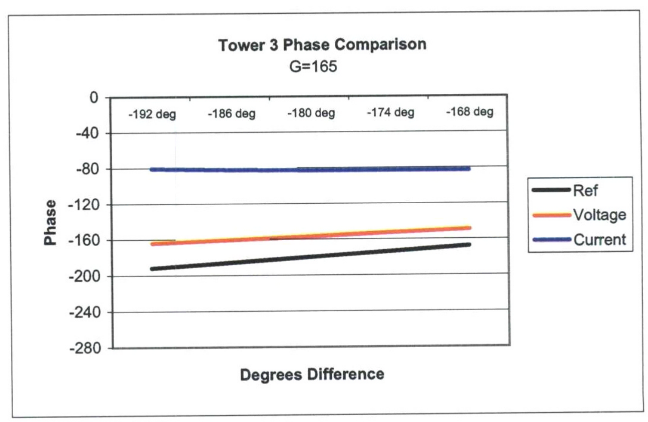
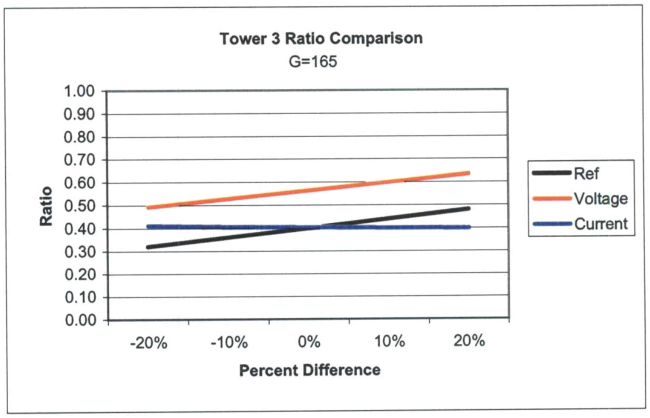


Fig. 11



Base sampled currents using TCT's are also subject to errors due to stray capacitance associated with the base insulator, the feed line over the ground plane, lighting transformers, iso-couplers and other devices mounted near the base of the antenna that are located between the TCT sampling location and the tower. Each source of stray capacitance at the base of a tower can be thought of as a circuit branch to ground. The current sampled by the TCT is then the total current delivered to the circuit and not the current flowing onto the tower. The phase angle measurement can also be modified because the "stray" currents are in quadrature with the current flowing "up" the radiator. For towers having heights less than approximately 105 electrical degrees or greater than approximately 210 electrical degrees, the base drive impedance is relatively low and therefore, the impact of the stray capacitance for most installations is minimal. For towers having heights between approximately 105 and 210 electrical degrees, the errors introduced by stray capacitance can be substantial.

Techniques have been developed, using a combination of moment method modeling and base impedance measurements, to derive an accurate set of relative base current magnitudes and phases that produce the desired directional pattern shape. These procedures are described in detail in the proposed rules presented to the FCC in September, 2007 [24] by the AM Directional Antenna Performance Verification Coalition.

The basic procedure is to develop a model of the antenna system using NEC, MININEC or other suitable moment method code. In order to produce the desired pattern shape in the moment method program, drive voltages that correspond to the desired radiated field parameters must be derived. This can be accomplished using techniques described by Trueman [39] and Westberg [40]. Certain commercially available computer codes, such as MININEC Broadcast Professional, have these algorithms built into the software.

The moment method model provides a good estimate of the base voltages and currents required to produce the desired directional pattern. In most cases however, the estimated base currents are not sufficient to produce a field pattern that meets FCC pattern tolerance requirements due to construction specific variables that are not fully incorporated into the model. These variables typically include stray capacitance, feed line inductance, actual velocity of propagation along the tower, guy cable effects, etc. However, by incorporating measured base impedance data into the model, each tower can be modified in the model to reflect the actual construction conditions at the site. This is accomplished by measuring the base impedance of each tower in the array with all other towers either shorted or opened at their bases. This condition is duplicated in the model for each tower and the modeled tower is modified until the model-derived base impedance is equal to the measured base impedance within a prescribed tolerance. Acceptable model parameter variations include: tower height and radius, and the addition of shunt capacitance and series inductance. Once all towers have been modified, the directional array model is re-run to establish a final set of relative base current magnitudes and phases at the TCT sample location. A full description of the procedures and parameter variation tolerances for this technique is contained in the proposed rules submitted by the AM Directional Antenna Performance Verification Coalition [24].

In summary, through use of moment method modeling in combination with measured impedance data, many of the past drawbacks to using TCT-based sampling systems have been fully overcome. However, best results are produced when these systems are used for towers having heights less than 120 degrees or greater than 190 degrees.

C Sample Case

In a recently completed project, the techniques described above, using moment method modeling in combination with measured impedance data, were used to set up an eight tower directional antenna system. The new station was diplexed onto the towers of an existing station located adjacent to the Florida Everglades. This afforded an excellent opportunity to verify the moment method techniques through a field strength measurement program in the absence of significant reradiating structures that that would otherwise distort the directional pattern.

In this case, the towers were of equal height, uniform cross-section, and base insulated. Non-conducting, Phillystran, guy cables were used on all towers. The tower heights at the operating frequency of the new station were 73.4 degrees. This tower height is well within the tower height range where TCT-based sampling works extremely well.

A model of the antenna system was developed using the NEC-4 computer code that had been specially modified to incorporate an algorithm that derives base drive voltages from radiated field parameters. Once all construction was completed at the site, impedance measurements were performed at the base of each tower with all other towers shorted at their base. Iterative changes to the modeled towers were made until the resulting model-derived base impedance of each tower matched the measured base impedance for the case where all other towers were shorted at their base. The directional model was then re-run with the modified towers to establish the relative magnitude and phase of the base currents required to produce the directional pattern.

Since the new station was diplexed onto the towers of an existing station, filters were installed at the base of each tower to isolate the transmission paths and mitigate interaction between the two stations. Although the capacitance associated with the filters could have been included in the model, it was decided that a simpler approach would be to temporarily relocate the TCT sample elements to the feed line location at the point at which the impedance measurements were performed; establish the NEC derived relative sample current parameters on the antenna monitor; and then return the TCT's to the permanent mounting location in the output branch of the ATU network (behind the filters). Once the TCT's were in their permanent position, a final set of antenna monitor parameters was recorded that corresponded to the NEC derived feed line parameters.

Table III below contains a comparison of the relative magnitude (ratio) and phase of the radiated fields (FCC field parameters), the NEC derived feed line currents, and the corresponding TCT measured currents at the output of the ATU network.

Table III

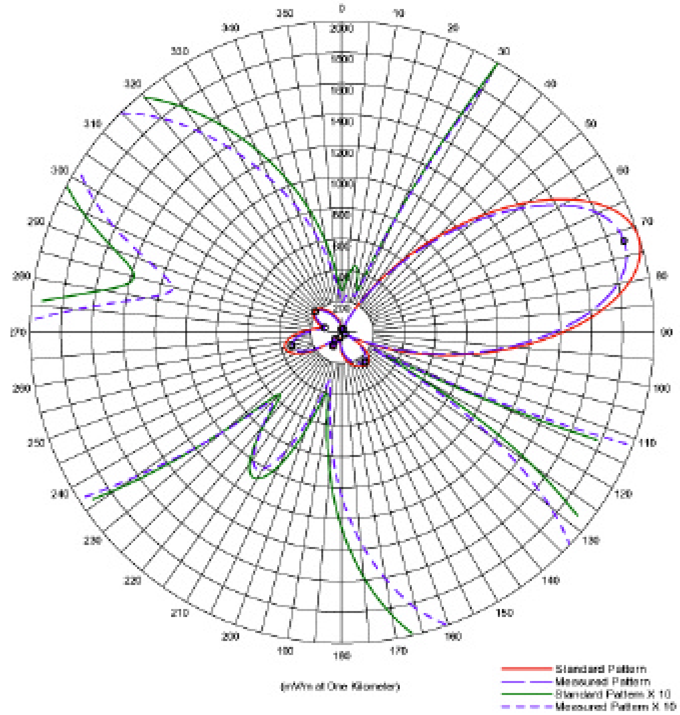
Tower	**FCC Field Parameters**		**NEC Derived Feed Line Currents**		**Measured ATU Output Currents**	
	Ratio	Phase	Ratio	Phase	Ratio	Phase
1	0.776	13.6	0.783	13.7	0.785	13.3
2	1.000	0.0	1.000	0.0	1.000	0.0
3	0.342	38.6	0.347	37.8	0.348	36.8
4	1.000	97.2	1.010	94.4	0.970	92.6
5	1.126	103.2	1.159	99.7	1.133	97.9
6	0.566	104.2	0.566	101.3	0.547	100.6
7	0.583	-37.4	0.549	-37.5	0.529	-38.4
8	0.745	99.0	0.736	96.0	0.718	94.2

A comparison of the NEC derived feed line parameters with the FCC field parameters indicates that the TCT-based sampling system provides a good approximation of the field parameters for the tower height of 73.4 degrees. Comparison of the measured relative ATU output currents with the corresponding feed line currents demonstrates the impact of the filter stray capacitance as discussed above. The impact of the filter stray capacitance, in this case, is relatively small due to the relatively low base drive impedances of the array.

After setting up the directional antenna system as described above, field strength measurements were performed in accordance with the procedures contained in the FCC's Rules. Non-directional and directional measurements were performed along twelve radial bearings including the bearings of the six pattern minima. A helicopter outfitted with a specially mounted and calibrated receive antenna and GPS receiver was used for all measurements.

The polar graphs of Figure 12 compare the measured pattern with the FCC authorized standard pattern [10].

Fig 12.



Note that the measured pattern shape, even in the highly suppressed null directions of the pattern, is in excellent agreement with the authorized pattern shape. Further, the measured radiated fields are within the authorized maximum radiation values (standard pattern fields) for all radial bearings except for the pattern minimum at 224.5 degrees, where the measured radiation exceeds the standard pattern radiation by 16%. It is believed that even this small perturbation in the measured pattern is the result of reradiation from sources external to the antenna array rather than the result of an error in the set-up procedure or in the TCT-based current samples.

This example case demonstrates that TCT-based sampling systems can be used to set up and verify complicated directional antenna systems when moment method modeling techniques are used to establish accurate estimates of the required feed line currents.

VI. Unequal Height Elements

A. Analysis

In the case where the antenna elements are of varying heights, the placement of sample loops is similar to the equal height element case covered in section V. However, there are some adjustments that need to be made to the expected measured current ratio, but not the phases, from these sample loops. If the elements have the same cross sectional area (towers have the same face width), the expected ratio will be adjusted by the ratio of the horizontal field developed from the varying heights of the elements.

For the single non-directional radiator, the horizontal field (in FCC nomenclature this is referred to as antenna efficiency) varies with height of the radiator. This can be calculated using basic electromagnetic physics or method of moments and is succinctly shown in FCC Figure 8. Table IV shows the current in the element at 1/3 of the height to produce a given field of 305.8 mV/m at 1 km.

Table IV

Element Height (Electrical Degrees)	Current (Amps)	Inverse Ratio of Current Referenced to 90°	Ratio of height Referenced to 90°	Agreement
70°	5.56	0.78	0.78	100.15%
80°	4.84	0.89	0.89	99.64%
90°	4.31	1.00	1.00	100.00%
100°	3.90	1.11	1.11	100.46%
110°	3.56	1.21	1.22	100.74%
120°	3.26	1.32	1.33	100.76%
130°	3.01	1.43	1.44	100.91%
140°	2.80	1.54	1.56	100.86%
150°	2.60	1.66	1.67	100.46%
160°	2.42	1.78	1.78	99.85%
170°	2.25	1.92	1.89	98.33%
180°	2.09	2.07	2.00	96.80%
190°	1.92	2.25	2.11	93.99%

As shown in this table, the current to produce a given field is inversely proportional to the element height and is a good approximation (within 1%) for elements up to 170°. For a first approximation for the desired antenna monitor parameters, the ratio of the current is adjusted by the ratio of the tower heights (for elements up to 170°). This however is not the full picture. The currents in the tower are also influenced by the mutual coupling of the elements of the antenna system.

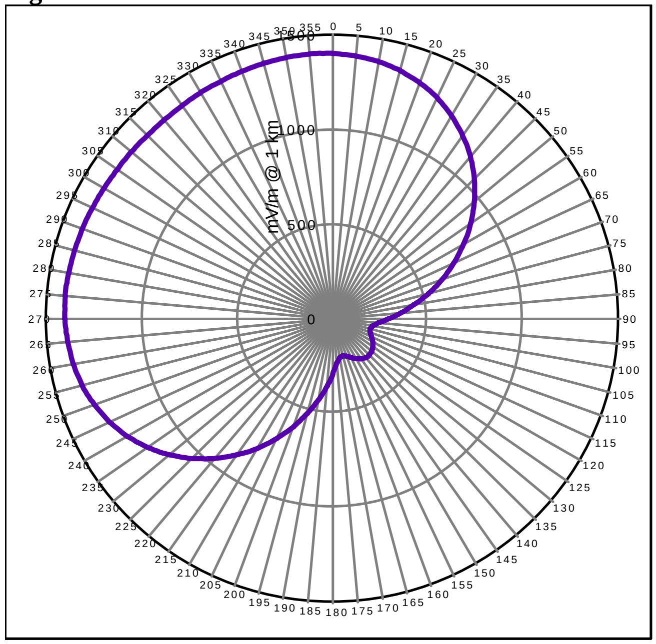
Consider the example of a system with the parameters shown in Table V:

Table V

Tower Number	Field	Phase	Spacing Distance	Bearing	Height
1	1.000	0.0°	0.0°	0.0°	90.0°
2	0.750	85.0°	110.0°	135.0°	130.0°

For a power of 10.0 kW, this facility will produce a horizontal pattern shown in Figure 13:

Fig. 13



It will have an RMS of 997.8 mV/m at 1 km and an RSS of 986.7 mV/m at 1 km for a RMS/RSS ratio of 0.99.

A moment method model shows that the currents at 1/3 of the element height to be:

Tower	Current Magnitude	Current Phase	Current Ratio
1	11.32	0.0	1.000
2	5.97	85.0	0.527

A first approximation of the antenna monitor ratio would expect a ratio of:

$$0.519 = 0.750 \cdot \left(\frac{90°}{130°} \right)$$

The model yields a ratio of 0.527, which is 1.5% high. As shown in this example, the best method of determining the design monitor system values is by use of moment method modeling with the sample loops at 1/3 of the element height.

VII. Elements With Different Cross Sectional Area

The electrical coupling of sample loops to the antenna element varies with the physical attributes of the antenna elements. For systems where the cross sectional area is the same for all elements, this can be ignored as the coupling factor is the same for each element. Where the coupling factor varies, each sample system must be calculated and compared, and the expected sample system parameters should be adjusted accordingly.

Sample loops couple to the typical triangular tower cross-section in the following manner. This deviation was provided by the late Robert M. Silliman, P.E. of Electronics Research Inc., see reference [21].

The voltage (V) induced in the sample loop is proportional to the current flowing (I) in the tower.

$$V = \frac{1}{3} \cdot I \cdot F \cdot 0.257 \cdot 10^{-6} \cdot H \cdot \left(\ln\left(\frac{S_5}{S_6}\right) + \ln\left(\frac{S_4}{S_7}\right) \right)$$

Fig. 14

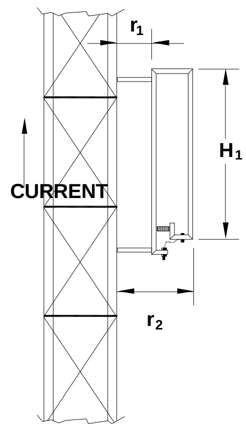
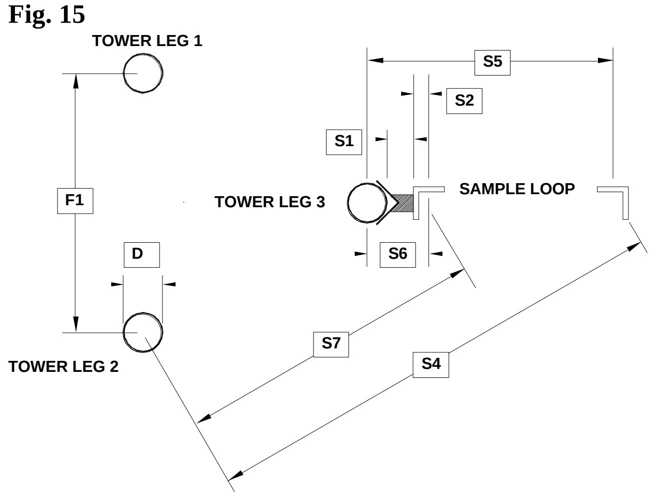


Fig. 15



Where:

I = Tower Current

F = Frequency in Hertz

H = Height of sample loop in meters

D = Diameter of tower leg in inches

W = Center to center leg spacing of tower (face width)

S_1 = Separation of the loop from the surface of the tower leg (inches or centimeters as units cancel)

S_2 = Half of the width of angle stock used to construct the loop (inches or centimeters as units cancel)

S_3 = Normal center to center of dimension of the loop

$$S_4 = \sqrt{\left(\frac{W}{2}\right)^2 + \left(W \sin 60^\circ + \frac{D}{2} + S_1 + S_2 + S_3\right)^2}$$

$$S_5 = \frac{D}{2} + S_1 + S_2 + S_3$$

$$S_6 = \frac{D}{2} + S_1 + S_2$$

$$S_7 = \sqrt{\left(\frac{W}{2}\right)^2 + \left(W \sin 60^\circ + \frac{D}{2} + S_1 + S_2\right)^2}$$

Where this is normalized to one amp, the relative coupling for each tower can be used to adjust the expected monitor system parameters.

For a system where there are two towers where one has the face width of 48 inches and the other has a face width of 60 inches (in the US structural steel is still dimensioned in inches) with the following parameters:

I = 1 Amp

F = 1,000,000 Hz

H = 1.219 m (48 inches)

D = 2 inches

W = 48 inches

S_1 = 4 inches

S_2 = 0.75 inches

S_3 = 10.5 inches

The coupling is 0.82 V/A for the 48-inch tower face, whereas it is 0.79 V/A for a 60-inch tower face. The expected current magnitude should be adjusted by this ratio. It is not expected that the phase would be effected by the varying coupling of the two sample loops.

VIII. Voltage Sampling

Either the voltage or current can be sampled to monitor the radiated parameters of directional antenna elements. It has been customary to monitor tower current for this purpose, as the currents flowing in the towers of an array more closely resemble the field parameters in ratio and phase than do the voltages. Each way has its advantages and disadvantages. Base current sampling is subject to stray capacitance effects that change the relationship of the monitored current to the radiating tower current, while voltage sampling is immune to that. Base voltages can vary over a much greater range than base currents within a directional antenna system, however, perhaps stretching the limits of accuracy of antenna monitors.

During studies related to the subject of proofing directional antenna patterns using moment method modeling, a fresh look was taken at voltage sampling. It has an advantage over current sampling in that modeled base voltages can be related directly to measured base voltages without regard to stray capacitance effects – or even circuits shunted across tower bases that change the current and impedance but not the base terminal voltage. Studies indicated that base voltage sampling will provide ranges of voltages that remain within the capabilities of contemporary antenna monitors and that follow changes in antenna element field parameters well for towers over 105 electrical degrees in height. Such use has been proposed for inclusion in the FCC Rules.

Should base voltage sampling be approved by the FCC, its implementation must await the development of base voltage sampling devices that can be calibrated against each other as base current sampling toroids can be today. Active sampling devices, powered with internal amplification, may be required to deliver the voltages needed by antenna monitors over 50-ohm coaxial cable to avoid the shunt loading that would take place with a simple voltage divider.

IX. Conclusion

We believe that careful method-of-moment modeling and antenna system tune-up with a thoroughly engineered sample system provides an antenna system that better matches the underlying antenna specifications that are derived by the allocation process. Experience has shown that this thoughtful design process has saved a great deal resources in the money, time and effort required for field iterations. The resulting antenna patterns have been confirmed numerous times with field measurements.

Acknowledgment

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