AM Antenna Computer Modeling

A Tutorial on Moment Method Computer Modeling for Performance Verification

Introduction

- AM directional patterns have long been adjusted and “proven” to be correct by magnetic field measurements.
- Such measurements are labor-intensive and time-consuming.
- Radial field measurements are error prone and often don’t give a true picture of the actual radiated directional pattern.
Introduction

• In 2008, the FCC enacted rules that would permit moment-method computer modeling of AM directional arrays in lieu of traditional proofs.
• These new rules have opened up an entirely new way of adjusting and proving AM directional patterns.
• 131 MoM applications have been processed by the FCC to date.

Why Model?

• Modeling solves, using a known and accepted method, the unknown current distribution variable.
• With the current distribution known, it is possible to solve for a set of operating parameters that will produce the proper directional pattern.
• Time and cost savings
Why Model?

• “Closed-ended” tune-up and proof process
• Eliminates the endless adjustment/proof process and “permanent STAs”
• More accurately adjusted patterns
• Reduced interference
• Calibrated sample systems
• Regular verification
• Eliminates most reradiator considerations

Sinusoidal Current Distribution

• Conventional AM antenna analysis has assumed sinusoidal current distribution
• Forward and reflected currents are attenuated as they propagate on a tower
• Summing the forward and reflected vectors together does not trace a sinusoidal curve
• Conventional analysis assumes uniform distribution for all array elements
Sinusoidal Current Distribution

- In the DA mode, there are two or more currents flowing in any array element
  - Transmit current
  - Receive currents from other array elements
- Actual element current at any point along a tower is the vector sum of the transmit and all the receive currents
- Current distributions on the array elements differ
- The relationships of element base or loop currents to far-field radiation are not known
Sinusoidal Current Distribution

• Tower currents required to produce a directional pattern could not be accurately calculated
• Theoretical parameters and “cut and try” were used with field measurements to “make” the pattern
• A lengthy process that was not always successful

Moment Method Modeling

• Each radiator is divided up into a number of segments
• Segment currents are solved numerically, taking into account:
  – Field coupling between segments on the radiator
  – Currents conducted from adjacent segments
• Produces an accurate representation of the actual tower current distribution
Advantages of Moment Method Modeling

- Accurately predicts current distribution
- Predicts tower voltages and currents that are directly related to DA parameters
- Accurately predicts base driving point impedances
- Allows for more accurate design of phasing and coupling system – less “fudge factor” is required since DPIs are known
Limitations of Traditional Field Measurements

- Actually magnetic (H) field measurements, not electric (E)
- Based on Maxwell’s Equations
- Describe the relationship between currents and fields
- Far-field equation is $E = 120\pi H$
- Ohm’s Law: $Z = E/H$, so $Z$ of free space is calculated as $120\pi$, or 377 ohms

Limitations of Traditional Field Measurements

- The $120\pi H$ relationship starts to fall apart at a distance from the antenna
- Radial field intensity measurement do not hold true except over smooth, uniform, high-conductivity terrain
- The basis for field intensity measurement makes several assumptions
  - Ignores conductivity changes
  - Ignores dielectric constant changes
  - Ignores diffraction
Limitations of Traditional Field Measurements

“Even the simple case of mixed conductivity with no diffraction and uniform dielectric constant is difficult…” - Ben Dawson, P.E. in *The Inadequacy of Magnetic Field Measurements for Antenna Performance Verification*

Problems with Maxwell’s Assumptions

- The earth is a sphere, not a plane as assumed
- The earth is not a perfect conductor
- The earth is not homogenous
- Maxwell’s $120\pi H$ relationship assumes:
  - Permittivity of $4\pi \times 10^7$ henrys/meter = $\mu$
  - Dielectric constant of $1/(36\pi \times 10^9)$ farads/meter = $e$
- The $E=120\pi H$ relationship is not a good fit beyond a certain distance from the antenna
Magnetic Field Disturbances

- Surface layer impedance dielectric discontinuities due to vegetation
- Conductivity changes due to soil or other surface geology changes
- Dielectric constant changes due to soil or surface geology changes
- Conductivity and dielectric constant changes due to bodies of water
- Diffraction effects due to topography
- Diffraction effects due to rugose topography
- Diffraction due to abrupt changes in conductivity/dielectric constant changes
- Electric field distortion due to electrically small vertical scatterers
- Magnetic field distortion due to finite sized loops of conducting material
- Absorption by poor conductor structures (i.e., wet concrete)
- Quasi-transmission line or ducting effects by urban streets with parallel rows of structures
- Reflection or multipath effects from slopes of good conductivity soil
- Quasi-free space propagation in curving sloped terrain
- Near-field effects from arrays of radiators
- Localized near-field effects from re-radiators
- Layered conductivity effects resulting from 1/R propagation

Analysis of Measured Data

- Enormous range of variability (>20 dB in many cases)
  - One of the primary reasons we analyze measured data graphically
- Distribution is not Gaussian
- Distribution is Rayleigh
- Arithmetic analysis will not in many cases provide a correct answer
- Solving for two variables
  - IDF and
  - Apparent conductivity (actually more than one variable)
Moment Method Basics

• The process starts with several assumptions:
  – The radius of the wires is very small with respect to the wavelength and the wire length
  – The wire must be subdivided into short segments so the radius is assumed small with respect to segment lengths.
  – The currents in the wires are axially directed (no circumferential currents on the wires)
• In AM broadcast work, all our work is over a ground plane (“method of images”)

Segmentation and Wire Radius

• Segment length, $\Delta$, should be less than about 0.05 wavelengths and longer than $10^{-3}$ wavelengths at the desired frequency.
• Extremely short segments (less than $10^{-3}\lambda$) should be avoided.
• The wire radius, $\alpha$, should be such that $\lambda/\alpha$ is greater than 30 and $2\pi(\alpha/\lambda)$ is much less than 1.
• The ratio $\Delta/\alpha$ must be greater than about 8.
• Segments may not overlap.
FCC Requirements on Wires

• The radius of each cylinder must be between 80% and 150% of the radius of a circle with a circumference equal to the sum of the widths (S) of the tower sides \((3S/2\pi)\).

• There must be no less than one segment per 10 electrical degrees of the tower’s physical height.

Segmentation

• More segments = better accuracy – to a point

• Convergence test can be used to find the point of diminishing returns

• Most broadcast antenna models of towers with reasonable heights work well with between 10 and 20 segments
NEC vs. MININEC

- NEC core puts voltage source in the center of a segment
- MININEC core puts voltage source at the end of a segment
- A NEC model of a broadcast tower will have its driving point located some distance up the tower rather than at the base
Directional Antenna Sources

- To model a DA, we need the source voltages and phases at each tower base
- Must translate the tower current moments to source parameters
- Requires summing the current moments of individual towers with a constant source driving each tower with the other bases shorted to ground
- Summed current moments are normalized to the reference tower to determine the field parameters

Determining DA Source Parameters

For a two-tower directional antenna:
\[ F_1 = V_{11}T_{11} + V_{12}T_{12} \]
\[ F_2 = V_{21}T_{21} + V_{22}T_{22} \]

With tower 1 driven and tower 2 shorted:
\[ F_1 = T_{11} \]
\[ F_2 = 0 \]

With tower 2 driven and tower 1 shorted:
\[ F_1 = 0 \]
\[ F_2 = T_{22} \]

For a directional array with n towers:
\[ F_1 = V_{11}T_{11} + V_{12}T_{12} + \ldots + V_{1n}T_{1n} \]
\[ F_2 = V_{21}T_{21} + V_{22}T_{22} + \ldots + V_{2n}T_{2n} \]
\[ \vdots \]
\[ F_n = V_{n1}T_{n1} + V_{n2}T_{n2} + \ldots + V_{nn}T_{nn} \]
\[ [F] = [T] \times [V] \]
\[ [S] = [T]^{-1} \]
\[ [V] = [F] \times [S] \]
Determining DA Source Parameters

- In the early days, consultants would iterate to find correct source parameters
  - Time consuming
  - Not very accurate
- Matrices are now used
- External programs (Westberg’s DRIVE)
- Internal programs (ACSModel)

Coordinate Systems

- NEC and MININEC cores use the spherical or Cartesian coordinate system
Coordinate Systems

- Broadcast engineers use the geographic coordinate system

- Some software “wrappers” convert from geographic to spherical internally
- For other programs or the cores themselves, the user must convert

\[
X = \text{Spacing} \cos(\theta) \\
Y = \text{Spacing} \sin(\theta) \\
Z = 0 \text{ or tower height in meters}
\]
Calibrating the Model

• Measure the base Z matrix
  – Measure each tower’s base Z with all other elements open or shorted
    • Depends on tower height
    • Use condition that best approximates detuned
    • Or do both

• Adjust the model until modeled base Z matrix matches measurements
  – Tower height
  – Tower radius

Model Radiation Pattern

• Broadcast antenna modelers don’t care too much about the model’s radiation pattern
  – The DA parameters determine the pattern

• Most “wrapper” software packages offer a radiation pattern output

• Useful for confirmation that the model was constructed correctly
• Should approximate the theoretical pattern
FCC Modeling Rules

• A method of moments program must be used.
• The model must be constructed in such a manner that it does not violate any of the internal constraints of the program used.
• Only arrays consisting of series-fed elements are eligible for the modeling option.
• Matrix impedance measurements must be made at the base and/or feed point of each array element.
• The physical characteristics of array elements (height and radius) may be varied to calibrate the model.
• Model impedances must agree with the measured impedance matrix within +/-2 ohms resistance and +/-4% reactance.

FCC Modeling Rules

• Actual spacings and orientations must be used.
• Towers may be modeled using vertical wires or with multiple wires representing legs and cross-members.
• Drive point impedances must be determined from the model output.
• The radius of each array element must be between 80% and 150% of the radius of a circle with a circumference equal to the sum of the widths of the sides.
• No less than one segment per 10 electrical degrees of the tower’s physical height must be used.
• Base calculations must be made at ground level or within one electrical degree of the actual feed point elevation.
FCC Modeling Rules

• For non-tapered towers, the modeled height of each element must be between 75% and 125% of the physical height.
• For tapered towers, stepped-radius wire sections may be used to simulate a tower's taper, or the tower may be modeled using wires for the legs and cross-members.
• The series feed impedance between the ATU output and tower base must be less than 10 uH unless measured higher.
• The shunt feed capacitance to model the base region effects must be less than 250 pF unless measured or specified by the manufacturer to be higher.
• If the shunt feed capacitive reactance is less than five times the magnitude of the base operating impedance, it must be considered in the model.
• The tower positioning must be confirmed post-construction by a surveyor or registered professional engineer.

FCC Modeling Rules

• Operating parameters must be determined from the output of the computer model.
• Samples may be current transformers or voltage sampling devices at the base of each element, or tower-mounted loops.
• Loops must be located at the elevation where the current in the tower would be at a minimum if the tower were detuned.
• Loops may be used only on towers of identical cross-sectional structure, including leg and cross-members.
• Loops on unequal height towers must be mounted with identical orientations at the proper elevations.
• If tower heights other than the physical heights are used in the model, loops must be mounted at the same percentage height as indicated in the model.
FCC Modeling Rules

- Sample lines must be equal in length within one electrical degree and characteristic impedance within two ohms, as confirmed by measurement.
- Base current sample transformers may be used for towers of 120 degrees or less or 190 degrees or greater in height.
- Base voltage sample devices may be used for towers of greater than 105 electrical degrees.
- Tower-mounted sample loops may be used on towers of any height.
- Base current sample transformers or voltage sampling devices must be calibrated against one another within the manufacturer’s specifications.
- Antenna monitor sample indications must agree with the model-determined ratios within +/-5% and with the model-determined phases within +/-3 degrees.
- Three reference field strength measurements must be made on each pattern minima and maxima radial.

Facility and Model Eligibility

- Only series-fed antenna elements
- Only accurate current/voltage samples
- The moment method model must match the measured base Z matrix
- For cylinder models, the effective radius assumption is limited to 80%-150% of the physical radius
- For cylinder models, the effective height assumption is limited to 75%-125% of the physical height
- At least one segment for each 10 degrees of physical height
- The model feedpoint must be at ground level or within one degree of physical elevation
- Series inductance must be 10 uH or less unless measured higher
- Parallel stray capacitance must be 250 pF or lower unless measured higher
Modeling Software

- NEC (NEC-2, NEC-4, etc.) and MININEC cores are in the public domain
- ACSModel is a MININEC 3 “wrapper”
- Expert MININEC Broadcast Professional (MBPro) is no longer in production
- A properly constructed model in all MININEC and NEC cores will result in roughly the same operating parameters

Measurements for Modeling

- Base impedance matrix measurements
- Sample system measurements/calibration
- Reference field strength measurements
- Biennial recertification
Base Impedance Matrix Measurements

- Measure at the ATU output
- Determine if lighting chokes, static drain chokes, etc. affect self-Z and disconnect if significant
- Measure with all other elements shorted, open or both depending on height
- It is useful to measure the series inductance of the feed tubing if possible

A Step-by-Step Moment Method Modeling Example (ACSMModel)
Base Region Circuit Model

• Because we cannot sample right at the tower base and must instead model upstream, in the ATU, we must take into account base-region reactances and their effect on the current
  – Base insulator capacitance
  – Feed series inductance
  – Lighting choke shunt inductance
  – Isocoupler shunt capacitance

Base Region Circuit Model

• A base region model and nodal analysis will account for these effects, which can be significant
• Westberg Consulting’s WCAPPPro works very well for this application
• Most of the base region effects can be calculated by hand, but a circuit model is much easier
Base Region Circuit Model

- The circuit model will show the impedance and current magnitude/phase shift through the base region “network”
- The same model is applied for the DA model
- The resulting operating parameters take into account the current magnitude/phase shift

The Traditional Sample System

- Tower-mounted loops or base current transformers
- Connect to antenna monitor using transmission lines (“sample lines”)  
  - Equal length in most cases
Modeled Array Sample System

• Accuracy and stability more important than with proofed array
• The means by which the array is set up and “proofed”
• Must measure voltage or current as it is modeled for each array element
• Tower-mounted loops at correct elevation or base current transformers, depending on tower height
• Samples must exclude external influences that cannot be modeled accurately
  – Skirt-fed towers
  – Slant wire feeds

Base Sampling

• TCTs must be at the same location that Z matrix was measured
• Must be removable for biennial calibration
• Construct and keep a calibration/test jig
Tower-Mounted Loop Sampling

- Loop must be mounted at the elevation where the tower current would be at a minimum if detuned
Loop Sampling

- Loops must be identical in construction and mounting
- Only on towers with identical legs and cross-sectional structure
- Leg-mounted and oriented perpendicular to the opposite face
- Electrically bonded to the tower
- Sample line can be bonded or insulated
Sample Lines

• Must be of equal electrical length (within 1 electrical degree)
• Must be of equal characteristic impedance (within 2 ohms)
• Must be “proofed” during initial setup and biennially thereafter

Sample Line Measurements

• Determine open-circuit resonant frequency closest to carrier to determine electrical length
• Measure at frequencies 45 degrees either side of this point to determine characteristic Z
• The best way to measure is with a network analyzer
Sample Line Measurements

- In an unterminated transmission line, impedance zeros will occur at odd multiples of 1/4\(\lambda\) (90°, 270°, 450°, etc.)
- Determine the odd multiple closest to carrier, then ratio that length to the length at the carrier frequency
- Start with the physical length
- Use \(F = 4 \times 984 / L / VF\) to find the approximate 1/4\(\lambda\) frequency for that length of line
Determining Electrical Length

- Determine which zero crossing is closest to carrier
- Electrical length is Carrier Freq/ Resonant Freq x Multiple (degrees)
- In the example: $670 / 600 \times 270 = 301.5$ degrees

Determining Characteristic Z

- Find the frequency that is $1/8\lambda$ (45 degrees) above and below the resonant frequency
- In the example:
  
  $270 - 45 = 225 \text{ deg.}$  
  $225 / 270 \times 600 = 500 \text{ kHz}$

  $270 + 45 = 315 \text{ deg.}$  
  $315 / 270 \times 600 = 700 \text{ kHz}$
Determining Characteristic Z

- Should be 90° either side of zero crossing closest to carrier on Smith chart
- Note the R and X at each frequency
- Calculate the magnitude
- The magnitude of the +/- 45° Z is the characteristic Z of the line
- Must be within 2 ohms of all other lines

Measuring Sample Lines into Sample Loops

- Measure unterminated sample line length when loops are installed/relocated
- Measure the Z looking into the sample lines with the loops connected
- Observe reflection coefficients
The differences in sample line length are 1/2 the calculated reflection coefficient angle differences.

Measuring Sample Lines into Sample Loops

- First, measure $Z_{IN}$ on the carrier frequency at antenna monitor end of sample line with line connected all the way to the loop
- Break the line at a convenient place (isocoil)
- Measure $Z_{IN}$ on the carrier frequency at that point looking towards the loop
- With line broken, measure unterminated electrical length back toward the antenna monitor
- Run each value of $Z_{IN}$ through the formula to find $K_1$ and $K_2$, then compute the difference
- Halve it to find the length difference
- Apply that factor to determine the total electrical length
FCC MoM Applications

• Must show every step of the modeling process
  – Base impedance matrix measurements
  – Model calibration
  – Base region circuit model
  – DA model
  – Sample system measurements/calibration
  – Reference field strength measurements

FCC MoM Applications

• If the pattern was not previously licensed pursuant to a traditional proof, a survey must be submitted showing that the as-built tower locations are within 1.5 electrical degrees of the design location
• Must show the current moments in the application
• A typical single-pattern MoM application will be 50+ pages in length
Traditional Methods of Analyzing Reradiators

- Fixed-loss evaluation
  - No loss
  - 50% loss
  - Represents “worst-case” conditions
  - Tended to overestimate reradiation
- NAB formula became “standard”
  - Tended to underestimate reradiation
- Field measurements were the deciding factor
- Modeling represents a better way

Modeling Reradiators

- Model the array per the procedure above, omitting the Z-matrix calibration.
- Model the reradiator in its proper location in the same model
- Use physical height and actual (or $3F/2\pi$) radius for potential reradiator
- Calculate the E-field along each radial of interest (“proof” radials) out to 10 km
- Plot the predicted E-field vs. distance on log-log paper with the standard pattern IDF line
- Graphically analyze the resultant to determine whether the standard pattern is exceeded
Reradiator exceeds standard pattern on radial

Radial below standard pattern with reradiator detuned.
Conclusion

• Note how E-field exceeds standard pattern close in even with detuned reradiator
• Conventional measurements would likely show a high IDF on the radial
• Worst-case reradiator caused only 0.8 dB excess radiation on radial
• Even with worst-case reradiator (close in on main lobe radial), little or no interference would result