FCC Method of Moments

Licensing AM
Directional Antenna Systems
The Task

- Comply with Construction Permit
  - Certify correct antenna location
  - Certify compliant pattern shape
  - Certify compliant pattern size

- Prepare FCC “302”

- Propose Verifiable Operating Parameters
Classic AM “Proof”

- **Construction Permit Requires**
  - Un-attenuated Inverse Field

- **Field Measurements Provide**
  - Attenuated Inverse Field

- **Need to Determine Ground Conductivity**
  - Build and measure a reference antenna
Classic AM “Proof”

Establish Pattern Shape and Size
- Measure directional antenna fields
- Apply ground conductivity correction
- Compare results to construction permit
- Adjust phasor controls
- Repeat as necessary…
- Perhaps hundreds of field measurements

A Time (and Money) Consuming Process
Classic “AM “ Proof

Pattern Shape
– A function of individual tower contributions
– Antenna monitor and sampling system

Antenna Monitor Parameters
– A “snapshot” on the last day of adjustment
– For reference, absolute value means little
– Filed with FCC “302” – License Parameters
Classic AM “Proof”

- **Long Term Maintenance**
  - “Periodic” License Parameter Readings
  - “Periodic” Monitor Point readings

- **Future Antenna System Changes**
  - More field measurements
  - Reference original ground conductivity
  - More repeat as necessary...
Could This Cumbersome Process be Improved?
FCC Method of Moments

**PRM 08-228 Second Report and Order**
- Originally FCC MM 93-177
- Originally Proposed in 1991
  - Hatfield and Dawson
  - duTreil, Lundin & Rackley
  - Lahm, Suffa & Cavell
  - Moffet, Larson & Johnson
  - Silliman & Silliman
- Available for Use in Filings Early in 2009
“Method of Moments”

Applicable to Engineering Problems
- Acoustics, Fluids, Mechanics
- Electromagnetics

Also Known as:
- Boundary Element Method
- Finite Element Method
- Finite Difference Method
“Method of Moments”

From “Wikipedia”:

- a numerical computational method of solving linear partial differential equations which have been formulated as integral equations (i.e. in boundary integral form).

- In electromagnetics, the more traditional term "method of moments" is often, though not always, synonymous with "boundary element method"
“Method of Moments”

In Plain English:

- Take a large complicated problem
- Cut it up into small, simpler pieces
- Solve the pieces (perhaps simultaneously)
- Recombine the solutions

The Numerical Electromagnetics Code

- Lawrence Livermore National Laboratory
“Method of Moments”

Continuous Current

Segmented Current
“Method of Moments”

NEC Modeled Antenna

¼ Wave Vertical
“Perfect” ground
10 Segments
Color indicates currents
“Method of Moments”

NEC Modeled Antenna

“Wire Frame” patterns
Polar plots
Antenna gain
Drive Point Impedance
about 36 j0 ohms
“Method of Moments”

NEC Modeled Antenna

5/8 Wave Vertical
Note Skywave Lobes

Drive Point Impedance
about 205 –j613 ohms
Back to “The Task”

Consider a Non-Directional “302”

– Determine Location: USGS Map
– Determine Pattern Shape

- Defined by geometry in horizontal plane
- Defined by formula in vertical plane

\[
f(\theta) = \frac{\cos(G \sin \theta) - \cos G}{(1 - \cos G) \cos \theta}
\]

*(FCC Rules 73.160)*
\[ f(\theta) = \frac{\cos(G \sin \theta) - \cos G}{(1 - \cos G)\cos \theta} \]
NDA Pattern Size

- **Un-attenuated Field (specified in mV/m)**
  - Difficult to directly measure

- **Proportional to Power (in Watts)**
  - Difficult to directly measure

- **Proportional to Base Current (in Amperes)**
  - Easily measured if base impedance is known
NDA Base Impedance

Determined by:
- Tower height, cross-section, material
- Base Insulator, lighting chokes
- Isocouplers, stray reactance, etc.

Measure Impedance
- Not expected to change under power
- Required base current can be calculated
NDA FCC “302”

- Location – coordinates from USGS Map
- Pattern Shape – geometry and formula
- Pattern Size – calculated base current

We have obtained the required technical information to prepare the license application without ever actually turning on the transmitter.
Back to “The Task”

- FCC Method of Moments for DA’s
  - Modeling the directional array
  - Verifying the mathematical model
  - Establishing operating parameters
  - Sampling system requirements
  - Long term maintenance
  - Additional FCC requirements
Modeling

- **NEC Model**
  - Mathematical description of array
  - Excite each tower, “float” all others
  - Create a tower array impedance matrix

- **Physical Array**
  - Measure each tower, “float” all others
  - Characterize any extra “stuff”

- “Massage” the Model
### GEOMETRY

Wire coordinates in degrees; other dimensions in meters

Environment: perfect ground

<table>
<thead>
<tr>
<th>wire</th>
<th>caps</th>
<th>Distance</th>
<th>Angle</th>
<th>Z</th>
<th>radius</th>
<th>segs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>none</td>
<td>181.2</td>
<td>120.2</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>181.2</td>
<td>120.2</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>none</td>
<td>366.4</td>
<td>116.6</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>366.4</td>
<td>116.6</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>none</td>
<td>123.8</td>
<td>213.6</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>123.8</td>
<td>213.6</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>none</td>
<td>201.7</td>
<td>144.9</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>201.7</td>
<td>144.9</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>none</td>
<td>375.6</td>
<td>130.1</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>375.6</td>
<td>130.1</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>none</td>
<td>90.</td>
<td>176.7</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90.</td>
<td>176.7</td>
<td>84.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example
Example

IMPEDANCE
  normalization = 50.

<table>
<thead>
<tr>
<th>freq (KHz)</th>
<th>resist (ohms)</th>
<th>react (ohms)</th>
<th>imped (ohms)</th>
<th>phase (deg)</th>
<th>VSWR</th>
<th>S11</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>source = 1</td>
<td>node 1, sector 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,180.</td>
<td>33.353</td>
<td>-7.1002</td>
<td>34.101</td>
<td>348.</td>
<td>1.5521</td>
<td>-13.297</td>
<td>-.20817</td>
</tr>
</tbody>
</table>

Model Impedance for all towers: 33.4 –j7.1 Ohms
Measured Impedance for tower 1: 39.1 +j60.2 Ohms

Not Acceptable
Verifying the Model

Other “Stuff” <  \( X_{ls} \)  \( X_{csc} \)  \( X_{cb} \) > Tower

- Feedline Inductance - \( X_{ls} \)
- Stray Capacitance - \( X_{csc} \)
- Base Insulator - \( X_{cb} \)

ATU Msmt. Point

Diagram showing electrical components and their connections.
Verifying the Model

With Series Inductance

\[ Z_{atu} = R_b + jX_b + jX_{ls} \]

With Shunt Capacitance

\[
\begin{align*}
R_{atu} &= \frac{R_b \ast X_{cs}^2}{R_b^2 + (X_b + X_{cs})^2} \\
X_{atu} &= \frac{jX_{cs} \ast (R_b^2 + X_b^2 + X_b \ast X_{cs})}{(R_b^2 + (X_b + X_{cs})^2)}
\end{align*}
\]
Verifying the Model

Change Velocity of Propagation
Slower velocity = taller tower

Measured Impedance for tower 1
39.1 +j60.2 Ohms

Model Impedance for Vp of 95.3% (105.2% height)
39.1 +j13.8 Ohms

Resistance is now Acceptable
GEOMETRY
Wire coordinates in degrees; other dimensions in meters
Environment: perfect ground

<table>
<thead>
<tr>
<th>wire</th>
<th>caps</th>
<th>Distance</th>
<th>Angle</th>
<th>Z</th>
<th>radius</th>
<th>segs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>88.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>none</td>
<td>181.2</td>
<td>120.2</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>181.2</td>
<td>120.2</td>
<td>88.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>none</td>
<td>366.4</td>
<td>116.6</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>366.4</td>
<td>116.6</td>
<td>88.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>none</td>
<td>123.8</td>
<td>213.6</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>123.8</td>
<td>213.6</td>
<td>88.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>none</td>
<td>201.7</td>
<td>144.9</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>201.7</td>
<td>144.9</td>
<td>88.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>none</td>
<td>375.6</td>
<td>130.1</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>375.6</td>
<td>130.1</td>
<td>88.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>none</td>
<td>90.</td>
<td>176.7</td>
<td>0</td>
<td>.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90.</td>
<td>176.7</td>
<td>90.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Example**

<table>
<thead>
<tr>
<th>Number of wires</th>
<th>= 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>current nodes</td>
<td>= 70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>minimum</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual wires</td>
<td>wire</td>
<td>value</td>
</tr>
<tr>
<td>segment length</td>
<td>4</td>
<td>8.8</td>
</tr>
<tr>
<td>radius</td>
<td>1</td>
<td>.29</td>
</tr>
</tbody>
</table>

**ELECTRICAL DESCRIPTION**

**Frequencies (KHz)**

<table>
<thead>
<tr>
<th>frequency</th>
<th>no. of</th>
<th>segment length (wavelengths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. lowest frequency</td>
<td>step</td>
<td>steps</td>
</tr>
<tr>
<td>1</td>
<td>1,180.</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Sources**

<table>
<thead>
<tr>
<th>source node</th>
<th>sector</th>
<th>magnitude</th>
<th>phase</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>voltage</td>
</tr>
</tbody>
</table>
# Example

## Lumped loads

<table>
<thead>
<tr>
<th>load</th>
<th>node</th>
<th>resistance (ohms)</th>
<th>reactance (ohms)</th>
<th>inductance (mH)</th>
<th>capacitance (uF)</th>
<th>passive circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>51</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>61</td>
<td>0</td>
<td>-10,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**IMPEDANCE**

normalization = 50.

<table>
<thead>
<tr>
<th>freq (KHz)</th>
<th>resist (ohms)</th>
<th>react (ohms)</th>
<th>imped (ohms)</th>
<th>phase (deg)</th>
<th>VSWR</th>
<th>S11</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,180</td>
<td>39.052</td>
<td>13.775</td>
<td>41.41</td>
<td>19.4</td>
<td>1.4853</td>
<td>-14.187</td>
<td>-.16884</td>
</tr>
</tbody>
</table>
**Example**

**CURRENT rms**

- **Frequency** = 1180 KHz
- **Input power** = 0.0113867 watts
- **Efficiency** = 100.%

Coordinates in degrees current

<table>
<thead>
<tr>
<th>no.</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>mag</th>
<th>phase</th>
<th>real</th>
<th>imaginary</th>
</tr>
</thead>
<tbody>
<tr>
<td>GND</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0170758</td>
<td>340.6</td>
<td>0.0161033</td>
<td>-5.68E-03</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>8.88</td>
<td>0.0170977</td>
<td>338.6</td>
<td>0.0159227</td>
<td>-6.23E-03</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>17.76</td>
<td>0.0166592</td>
<td>337.4</td>
<td>0.0153845</td>
<td>-6.39E-03</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>26.64</td>
<td>0.0158121</td>
<td>336.5</td>
<td>0.0144999</td>
<td>-6.31E-03</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>35.52</td>
<td>0.0145774</td>
<td>335.7</td>
<td>0.0132834</td>
<td>-6.0E-03</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>44.4</td>
<td>0.012979</td>
<td>335</td>
<td>0.0117601</td>
<td>-5.49E-03</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>53.28</td>
<td>0.011045</td>
<td>334.3</td>
<td>9.96E-03</td>
<td>-4.78E-03</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>62.16</td>
<td>8.8E-03</td>
<td>333.8</td>
<td>7.9E-03</td>
<td>-3.89E-03</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>71.04</td>
<td>6.28E-03</td>
<td>333.2</td>
<td>5.61E-03</td>
<td>-2.83E-03</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>79.92</td>
<td>3.46E-03</td>
<td>332.7</td>
<td>3.08E-03</td>
<td>-1.59E-03</td>
</tr>
<tr>
<td>END</td>
<td>0</td>
<td>0</td>
<td>88.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Verifying the Model

Adjust Tower Impedance Matrix

- “Massage” model to agree with values measured at the ATU output
  - Adjust model height (velocity of propagation)
  - Add lumped feed inductance (series)
  - Compensate for base insulator capacitance
- Repeat for each tower in array
- An iterative process
FCC Requirements

– Only arrays with series-fed elements

– At least 1 segment per 10 degrees height

– Modeled radii between 80% and 150% of circle of circumference equal to sum of sides

– Modeled height between 75% and 125% of physical tower height
FCC Requirements

- Tapered towers may be modeled as a series of stepped cylinders (wedding cake)

- Actual tower spacings and orientation must be used in the model
  
  This needs to be confirmed by a surveyor

- Lumped series inductance limited to 10 uH

- Lumped shunt capacitance limited to 250 pF
FCC Requirements

– Other base region components (lighting chokes, etc.) must be specifically measured and included in the model

– Measured impedance matrix must agree with moment method model within +/- 2 ohms or +/- 4%, which ever is greater
Example

Two turn lightning loops placed in tower feeds (all 7 towers)

Loops measured between j33.9 and j46.6 Ohms (4.6 – 6.3 uH)
### Model R’s now within 0.1 Ohm of measured R’s
### Model tower heights at 104% to 107% of actual
### Model lumped inductance less than 10 uH

<table>
<thead>
<tr>
<th>Tower</th>
<th>Msd</th>
<th>Msd</th>
<th>Msd Feed</th>
<th>Calc</th>
<th>Model</th>
<th>Model</th>
<th>Model</th>
<th>Model</th>
<th>Model</th>
<th>Model</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Height</td>
<td>% of 84.6</td>
<td>R</td>
<td>R % dev</td>
<td>X</td>
<td>X dev</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>39.1</td>
<td>60.2</td>
<td>40.3</td>
<td>19.9</td>
<td>88.8</td>
<td>105.2</td>
<td>39.1</td>
<td>-0.12</td>
<td>13.8</td>
<td>-6.15</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>39.8</td>
<td>61.0</td>
<td>44.5</td>
<td>16.5</td>
<td>88.5</td>
<td>104.9</td>
<td>39.8</td>
<td>-0.09</td>
<td>11.6</td>
<td>-4.89</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>38.7</td>
<td>50.0</td>
<td>33.9</td>
<td>16.1</td>
<td>88.2</td>
<td>104.5</td>
<td>38.6</td>
<td>-0.20</td>
<td>9.8</td>
<td>-6.26</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>37.6</td>
<td>45.8</td>
<td>34.8</td>
<td>11.0</td>
<td>88.0</td>
<td>104.3</td>
<td>37.6</td>
<td>-0.05</td>
<td>8.3</td>
<td>-2.67</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>39.7</td>
<td>60.2</td>
<td>46.6</td>
<td>13.6</td>
<td>88.6</td>
<td>105.0</td>
<td>39.6</td>
<td>-0.17</td>
<td>12.0</td>
<td>-1.56</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>38.7</td>
<td>43.2</td>
<td>38.1</td>
<td>5.1</td>
<td>88.2</td>
<td>104.5</td>
<td>38.7</td>
<td>0.03</td>
<td>10.0</td>
<td>4.92</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>39.0</td>
<td>58.5</td>
<td>38.6</td>
<td>19.9</td>
<td>90.2</td>
<td>106.9</td>
<td>39.0</td>
<td>-0.12</td>
<td>20.9</td>
<td>0.94</td>
<td></td>
</tr>
</tbody>
</table>
Modeling

Pattern Shape Defined by Formula

\[
E(\phi, \theta)_{\text{theo}} = k \sum_{i=1}^{n} E_i * f_i(\theta) \angle (S_i \cos \theta \cos (\phi_i - \phi) + \phi_i)
\]

\[(FCC \text{ Rules 73.150})\]

The Sum of Individual Tower Fields
- Field ratio and phase for each tower
- Specified in construction permit
Modeling

Measuring the Tower Field is Difficult
– As with NDA, measure currents, however...

*Establishing Tower Drive Impedances in Directionals is Very Difficult*

Impedance is really “Volts-per-Ampere”
– Tower drive impedance is a summation
– Self-impedance plus other “volts-per-ampere”
Modeling

Credit to Jerry Westburg:
- “Matrix Method for Relating Base Current Ratios to Field Ratios of AM Directionals”

Calculate Drive Impedances and Currents
- Verified NEC mathematical model
- Field ratios from construction permit
MEDIUM WAVE ARRAY SYNTHESIS FROM FIELD RATIOS

Frequency = 1180 KHz

<table>
<thead>
<tr>
<th>tower</th>
<th>magnitude</th>
<th>phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0.894</td>
<td>109.2</td>
</tr>
</tbody>
</table>

VOLTAGES AND CURRENTS - rms

<table>
<thead>
<tr>
<th>node</th>
<th>magnitude</th>
<th>phase (deg)</th>
<th>magnitude</th>
<th>phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,730.9</td>
<td>40.8</td>
<td>27.9853</td>
<td>5.2</td>
</tr>
<tr>
<td>61</td>
<td>419.553</td>
<td>128.1</td>
<td>26.2662</td>
<td>111.1</td>
</tr>
</tbody>
</table>

Sum of square of source currents = 2,948.56
Total power = 50,000. watts

Normalize phase (111.1 – 5.2), Tower 7 Phase = +105.9°
Ratio current (26.2662 / 27.9853), Tower 7 Ratio = 0.939
### MEDIUM WAVE ARRAY SYNTHESIS FROM FIELD RATIOS

<table>
<thead>
<tr>
<th>tower</th>
<th>magnitude</th>
<th>phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.438</td>
<td>-6.9</td>
</tr>
<tr>
<td>2</td>
<td>1.</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>.523</td>
<td>16.7</td>
</tr>
<tr>
<td>4</td>
<td>.418</td>
<td>64.9</td>
</tr>
<tr>
<td>5</td>
<td>.99</td>
<td>99.5</td>
</tr>
<tr>
<td>6</td>
<td>.549</td>
<td>122.</td>
</tr>
</tbody>
</table>

### VOLTAGES AND CURRENTS - rms

<table>
<thead>
<tr>
<th>node</th>
<th>magnitude</th>
<th>phase (deg)</th>
<th>magnitude</th>
<th>phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>246.145</td>
<td>333.3</td>
<td>3.69944</td>
<td>.1</td>
</tr>
<tr>
<td>11</td>
<td>415.624</td>
<td>17.3</td>
<td>7.85442</td>
<td>5.5</td>
</tr>
<tr>
<td>21</td>
<td>184.362</td>
<td>23.4</td>
<td>4.18681</td>
<td>21.5</td>
</tr>
<tr>
<td>31</td>
<td>38.5047</td>
<td>339.6</td>
<td>3.44322</td>
<td>65.1</td>
</tr>
<tr>
<td>41</td>
<td>56.0734</td>
<td>45.7</td>
<td>8.02852</td>
<td>100.</td>
</tr>
<tr>
<td>51</td>
<td>13.2224</td>
<td>329.3</td>
<td>4.43341</td>
<td>121.8</td>
</tr>
</tbody>
</table>

Sum of square of source currents = 378.234
Total power = 5,000. watts
**Example**

### Day Pattern - 50 KW.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field</td>
<td>Phase</td>
<td>R</td>
<td>X</td>
<td>Current</td>
<td>Phase</td>
<td>Ratio</td>
<td>Phase</td>
</tr>
<tr>
<td>(Ref) 1</td>
<td>1</td>
<td>0</td>
<td>50.323</td>
<td>35.981</td>
<td>27.9982</td>
<td>5.2</td>
<td>1.000</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.894</td>
<td>109.2</td>
<td>15.269</td>
<td>4.6807</td>
<td>26.2882</td>
<td>111.1</td>
<td>0.939</td>
<td>105.9</td>
</tr>
</tbody>
</table>

### Night Pattern - 5 KW.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field</td>
<td>Phase</td>
<td>R</td>
<td>X</td>
<td>Current</td>
<td>Phase</td>
<td>Ratio</td>
<td>Phase</td>
</tr>
<tr>
<td>1</td>
<td>0.438</td>
<td>-6.9</td>
<td>59.424</td>
<td>-31.339</td>
<td>3.69731</td>
<td>0.1</td>
<td>0.471</td>
<td>-5.4</td>
</tr>
<tr>
<td>(Ref) 2</td>
<td>1</td>
<td>0</td>
<td>51.818</td>
<td>10.779</td>
<td>7.85258</td>
<td>5.5</td>
<td>1.000</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.523</td>
<td>16.7</td>
<td>44.009</td>
<td>1.4782</td>
<td>4.18673</td>
<td>21.5</td>
<td>0.533</td>
<td>16.0</td>
</tr>
<tr>
<td>4</td>
<td>0.418</td>
<td>64.9</td>
<td>0.8838</td>
<td>-11.147</td>
<td>3.44338</td>
<td>65.1</td>
<td>0.439</td>
<td>59.6</td>
</tr>
<tr>
<td>5</td>
<td>0.99</td>
<td>99.5</td>
<td>4.0698</td>
<td>-5.6732</td>
<td>8.03095</td>
<td>100</td>
<td>1.023</td>
<td>94.5</td>
</tr>
<tr>
<td>6</td>
<td>0.549</td>
<td>122</td>
<td>-2.6455</td>
<td>-1.3779</td>
<td>4.43277</td>
<td>121.8</td>
<td>0.564</td>
<td>116.3</td>
</tr>
</tbody>
</table>

*Operating Parameters Calculated!*
Example

CP pattern versus NEC generated pattern
Example

CP pattern versus NEC generated pattern
We have obtained most of the required technical information to prepare the license application without turning on the transmitter. 

But, we still need to tune up the phasor...
Example

Tune-up:

- Day, 2 towers - about 4 hours
- Night, 6 towers - about 4 days
  - More fussing required at ATU’s
  - Some very low tower drive impedances

- Measurements to characterize the array
- Time to “massage” the model
FCC Requirements

Determining “Proper Adjustment”

- Correlation of the Method of Moments parameters and antenna monitor indications
  - Ratio +/- 5%
  - Phase +/- 3 degrees
- Correlation of Method of Moments and measured matrix impedances
  - Within +/- 2 ohms, +/- 4% for both resistance and reactance
Sampling System

“Classic” Proof
- Pattern adjusted by field measurements
- Antenna parameters are a “snapshot”
  Values are a *relative* indication of operation

Method of Moments Proof
- Pattern adjusted by antenna parameters
  Values are an *absolute* indication of operation
Sampling System

The Sampling System Must be Accurate
- Verified equal phase shift in all lines
- Verified equal impedance for all lines
- Verified equal sample toroid characteristics
- Verified accurate antenna monitor

System Measurements
- Network analyzer or impedance bridge
Sample Line Verification

- Line Open Circuit
- Tuneable RF source
- Oscilloscope
- GR 916AL Bridge

Diagram:
- RF Generator
- Wideband Detector
- RF Bridge
- Open Circuit
Sample Lines

Verifying Length and Impedance

- Find nearest sample line resonant frequency
  - Open circuit line
  - Shorts occur at odd multiples of $\frac{1}{4}$ wavelength
  - Ratio frequencies for sample line length at carrier
- Measure lines at + and $-\frac{1}{8}$ wavelength

$$Z_0 = \sqrt{\left(\sqrt{\frac{R_+^2}{4} + \frac{X_+^2}{4}}\right) \ast \left(\sqrt{\frac{R_-^2}{4} + \frac{X_-^2}{4}}\right)}$$
## Sample line measurements with GR-916AL bridge

### Null measurements made with far line end OPEN

<table>
<thead>
<tr>
<th>Tower</th>
<th>Null #1</th>
<th>Null #2</th>
<th>Null #3</th>
<th>1180 KHz</th>
<th>Offset</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90 deg</td>
<td>270 deg</td>
<td>450 deg</td>
<td>Length</td>
<td>+45 deg</td>
<td>-45 deg</td>
</tr>
<tr>
<td>1</td>
<td>318.0</td>
<td>961.0</td>
<td>1609.3</td>
<td>331.5</td>
<td>1121.2</td>
<td>800.8</td>
</tr>
<tr>
<td>2</td>
<td>318.0</td>
<td>961.2</td>
<td>1609.6</td>
<td>331.5</td>
<td>1121.4</td>
<td>801.0</td>
</tr>
<tr>
<td>3</td>
<td>318.0</td>
<td>961.2</td>
<td>1609.5</td>
<td>331.5</td>
<td>1121.4</td>
<td>801.0</td>
</tr>
<tr>
<td>4</td>
<td>318.0</td>
<td>961.1</td>
<td>1609.6</td>
<td>331.5</td>
<td>1121.3</td>
<td>800.9</td>
</tr>
<tr>
<td>5</td>
<td>318.0</td>
<td>961.1</td>
<td>1609.5</td>
<td>331.5</td>
<td>1121.3</td>
<td>800.9</td>
</tr>
<tr>
<td>6</td>
<td>318.1</td>
<td>961.3</td>
<td>1609.9</td>
<td>331.4</td>
<td>1121.5</td>
<td>801.1</td>
</tr>
<tr>
<td>7</td>
<td>318.0</td>
<td>961.1</td>
<td>1609.6</td>
<td>331.5</td>
<td>1121.3</td>
<td>800.9</td>
</tr>
</tbody>
</table>
### Sample line measurements with GR-916AL bridge

#### Null measurements made with far line end OPEN:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower</td>
<td>R (+45)</td>
<td>X (+45)</td>
<td>R (-45)</td>
<td>X (-45)</td>
<td>line Z</td>
</tr>
<tr>
<td></td>
<td>ohms</td>
<td>ohms</td>
<td>ohms</td>
<td>ohms</td>
<td>ohms</td>
</tr>
<tr>
<td>1</td>
<td>5.6</td>
<td>48.1</td>
<td>4.4</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>2</td>
<td>5.6</td>
<td>48.1</td>
<td>4.3</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>3</td>
<td>5.7</td>
<td>48.1</td>
<td>4.3</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>48.1</td>
<td>4.3</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>5</td>
<td>5.7</td>
<td>48.1</td>
<td>4.3</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>6</td>
<td>5.6</td>
<td>48.1</td>
<td>4.3</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
<tr>
<td>7</td>
<td>5.7</td>
<td>48.1</td>
<td>4.4</td>
<td>-50.6</td>
<td>49.6</td>
</tr>
</tbody>
</table>
Sample System

- Verifying Toroids
  - Build a test fixture
  - Common RF current
  - Toroids closely spaced
  - Use antenna monitor for measurement

- Verifying Sample Loops
  - More complicated
  - FCC Rules 73.151, FCC 08-228
Toroid Verification

Toroids

RF Source → Dummy Load

Test Lines

Antenna Monitor
Example

- **Toroid Test Fixture**
  - Always ground toroids!
  - Always terminate!

- **Operate into Load**

- **Used Potomac 1900**
  - Equal Length cables
  - 1.5 RF Volts minimum
FCC Requirements

– Sample line lengths must agree within 1 electrical degree

– Sample line characteristic impedances must agree within 2 ohms

– Toroids allowed for tower heights less than 120 degrees or greater than 190 degrees
Field Measurements

Some Field Measurements Still Required
- On pattern minima and maxima
- Three points per radial
- Only reference measurements

Not Monitor Points, No Regular Readings
- However, these measurements (and some others) must be periodically repeated
Maintenance

At Least Once Every 24 Months

- Sampling system
  - Recertify toroid performance
    - Common reference signal calibration
  - Recertify sample line performance
    - Length and characteristic impedance
- Repeat reference field measurements
- Retain in Public Inspection File
The Decision

Method of Moments

or

“Classic” Proof