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Insulated Wire Models — Lossless Insulations

Methods for modeling single and multiple-layer insulated wire in antenna modeling programs.

Introduction

Amateur antennas often incorporate insulated wire, i.e., wire covered with a dielectric or magnetic material. The cover is sometimes called cladding, coating, sheath, shell, or wrapping. The common term among amateur antenna modelers is insulation. Part one of this two-part article describes methods for modeling both single-layer and multiple-layer insulated wires in common antenna modeling programs. A variety of insulation materials are allowed, including dielectric, magnetic, and general magneto-dielectric materials. This article focuses on lossless insulation. The methods are accurate for modeling wires covered by low-loss dielectric insulation such as common plastics.

Lossy insulations can sometimes be described by electric and magnetic loss tangents. We address only the lossless case here and defer the subject of lossy materials to a future article. The formulas presented here are new and have not been published before. To facilitate understanding, brief derivations of key formulas are included. This article is intended to be both an instructive tutorial and a useful reference for antenna modelers.

Some programs, notably *NEC-3*, *NEC-4*, and *AN-SOF*, incorporate an insulated wire capability in their calculating engine but are generally limited to modeling single-layer dielectric insulation. Other thin-wire calculating engines, notably *NEC-2*, *NEC-5*, and *MiniNEC*, do not have native capability to model insulated wire. For these programs, an aftermarket user interface GUI program, such as *4nec2*, *EZNEC*, or *MMANA-GAL*, can provide an insulated wire capability that the main calculating engine lacks. It is therefore important to know how to model insulated wire both for using programs that lack the capability and for getting an independent check on those programs that do. Below we describe the main methods for modeling insulated wires: methods that are built-in and integrated with a Method of Moments (MoM) code, which modify the moment method's impedance or interaction matrix directly, and methods that are indirect and may be used when the MoM impedance or interaction matrix is inaccessible. All methods assume insulation is electrically thin, not thick.

Figure 1 shows the cross-section of a wire that has one layer of insulation. Conductor radius is a. Insulation outer radius is b. Insulation thickness is $b - a$. The modeling methods described here require that insulation thickness be much smaller than a wavelength in the medium of the insulation. This requirement is necessary to ensure higher-order cavity modes are cut off. There is no requirement that the insulation thickness be small compared to the conductor radius. Thick insulation is allowed as long as it is electrically thin.

Induced EMF Method for Dipoles

One of the earliest methods of computing antenna impedance is the induced e.m.f. method (IEMF) developed by A.A. Pistolkors **[2]** and P.S. Carter **[3]**. The method is a degenerate form of MoM in which there is a single segment and global, sinusoidal basis function. Because of the single segment, this method applies only to straight linear wires. J.P.Y. Lee and K.G. Balmain **[27]** show for a symmetric, center-driven dipole made of an insulated, infinite-conductivity wire in free space, the self-impedance of the single-segment dipole is given by

$$Z = Z_{IEMF} + Z_{correction}$$

The correction term $Z_{correction}$ is a pure reactance, which depends on dimensions, dielectric constant, and is a product of positive factors

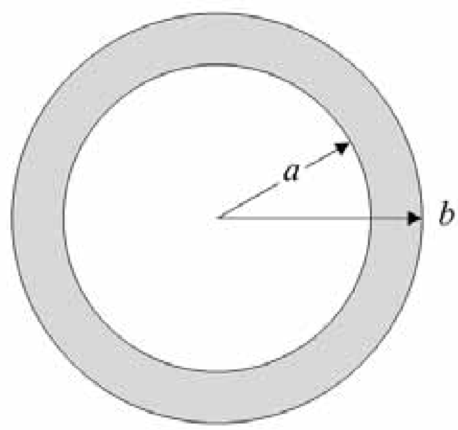

Figure 1 – Cross-section geometry of a single-layer insulated wire

$$Z_{correction} = j\eta\left(\frac{k\,l}{2\pi\sin^2(k\,l)}\right)\left(1+\frac{\sin(2k\,l)}{2k\,l}\right)\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$$

where

η = Characteristic impedance of free space, 376.73 ohms
k = Propagation phase constant (wave number) in radians per meter
l = Dipole (segment) half-length in meters
ε_r = Dielectric constant of the insulation
a = Outer radius of the metal wire
b = Outer radius of the dielectric insulation
$\ln(\cdot)$ = Natural (base e) logarithm function

Because all factors are positive, the reactance is "inductive" although its frequency dependence is different from the linear proportionality of an inductor. Consequently, the effect of insulation is to lower a dipole's resonant frequency (and increase its anti-resonant frequency) compared to that of a bare-wire dipole of the same length.

One might think to modify the IEMF method to account for insulated wire by substituting an equivalent bare wire radius into Carter's IEMF formula by using one of the equivalent wire approaches described below. However, when treating a dipole as a single long segment, the IEMF method does not give the correct current distribution, nor does it take into account other effects such as phase delay, distributed inductance, ac resistance, complicated shaped wires, or parasitic elements. Such effects are taken into account by using a many-segment model.

Direct Method-of-Moments Methods

Richmond: J.H. Richmond treats the perturbation as an additive correction to the MoM impedance (or "interaction") matrix **[20]**, **[21]**, **[23]**. Richmond's approach does *not* add inductance loading to segments. A modified current distribution on insulated segments is determined from a segment-by-segment traveling wave model that takes into account increased phase constant (reduced velocity factor) on each insulated segment. The perturbations affect the entire MoM impedance matrix, not just its diagonal elements as loading would do.

$$\mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1N} \\ \vdots & \ddots & \vdots \\ z_{N1} & \cdots & z_{NN} \end{bmatrix} = \mathbf{Z}_{\text{bare wire}} + \mathbf{Z}_{\text{correction}}$$

where **Z** is the $N \times N$ MoM mutual impedance matrix, and N is the number of segments in the model. To determine the correction, Richmond uses two electromagnetic theorems: the volume equivalence principle and the surface equivalence principle. First, the dielectric medium is replaced by air containing volumetric source field $\mathbf{J}_V$. Then the volumetric source field is replaced by an equivalent surface source field $\mathbf{J}_S$ defined on the outer surface of the insulation. Finally, an integration is performed over the length of the segment to obtain the impedance correction.

NEC-4.2: G.J. Burke adopted Richmond's method into *NEC-3* and *NEC-4,* calling it the IS (for *insulation*) command. He improved Richmond's model and made numerical comparisons against the method of Popović, et al., **[23]**, **[28]**, **[34]**. Geometry is not changed; lengths and diameters of insulated wires are not changed. Instead, additive correction terms are calculated for the impedance matrix. The IS algorithm is very similar to that of Richmond and Newman **[23]**. Wire dimensions are not altered, and segment loading is not used. Instead, the impedance matrix correction terms are computed and applied to the MoM interaction matrix directly.

AN-SOF: The insulation approach in *AN-SOF* is to load segments. Wire length and diameter are not modified. *AN-SOF* calculates a distributed load, similar to how conductivity or resistivity is added to wires. Each wire segment is loaded with an impedance value, determined by multiplying the distributed impedance per unit length (Z_{wire} in ohms per meter) by the segment's length, where Z_{wire} is computed from the transfer impedance between the external medium, typically air or vacuum, and the internal medium (conductor) with the dielectric layer in between. The formula used is proprietary. The correction is to the diagonal elements of the MoM interaction (or impedance) matrix and may be written as

$$\mathbf{Z} = \mathbf{Z}_{\text{bare wire}} + \mathbf{Z}_{\text{self load}} = \begin{bmatrix} z_{11} & \cdots & z_{1N} \\ \vdots & \ddots & \vdots \\ z_{N1} & \cdots & z_{NN} \end{bmatrix} + \begin{bmatrix} z'_{11} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & z'_{NN} \end{bmatrix}$$

Indirect "Equivalent Wire" Methods

Indirect methods are useful for third-party or after-market GUI programs. One simple approach to modeling insulated wires is to replace them with *equivalent* uninsulated wires. Three different methods for specifying equivalent wires are described below. The methods have different accuracies, which are discussed in a later section.

Method 1: The first method is due to L.B. Cebik, W4RNL, and is used in *4nec2* with the *NEC-2* engine **[57]**, **[69]**. Given an insulated wire having conductor radius a and insulation outer radius b, the equivalent wire is an uninsulated wire having the same radius a plus distributed inductive loading in the amount

$$L = \frac{\mu_0}{2\pi}\left(\frac{b}{a}\varepsilon_r\right)^{\frac{1}{12}}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right) \text{ henries per meter}$$

where

L = Distributed inductance in henries per meter
ε_r = Dielectric constant of the insulation
μ_0 = Magnetic permeability of vacuum, 4π×10−7 henries per meter
ε_r = Outer radius of the metal wire
a = Outer radius of the metal wire
b = Outer radius of the dielectric insulation
$\ln(\cdot)$ = Natural (base e) logarithm function

The equivalent wire has the same length and conductivity as the wire it replaces. This method is not based on electromagnetic theory but comes from an ad hoc curve fit to the insulated wire correction inside *NEC-4*. Absolute accuracy has not been established.

Method 2: The second method is due to A.S. Yurkov, RA9MB, and is used in *MMANA* with the *MiniNEC* engine **[65]**, **[85]**. According to this method, the equivalent wire is an uninsulated wire having radius b (instead of a) plus distributed inductive loading in the amount

$$L = \frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r k_{abs}^2}\right)\ln\left(\frac{b}{a}\right) \text{ henries per meter}$$

The equivalent wire has the same length and conductivity as the wire it replaces. This method is based on electromagnetic theory and is believed to be more accurate. However, this method has the disadvantage that the distributed inductance depends on k_{abs}, which is neither a physical constant nor a geometric dimension, but rather is an indeterminate variable for which no formula is given.

Method 3: The third method is due to the author, K6OIK, **[74]**, **[86]**, **[87]**, **[89]**, **[90]**. According to this method, the equivalent wire is an uninsulated wire having an intermediate outer radius a' plus distributed inductive loading and modified conductivity. The radius and loading are given by

$$a' = a\left(\frac{b}{a}\right)^{\left(1-\frac{1}{\varepsilon_r}\right)}$$

$$L = \frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right) \text{ henries per meter}$$

Skin effect loss is accounted for by decreasing the metal conductivity to

$$\sigma'_{effective} = \sigma\left(\frac{a}{b}\right)^{2\left(1-\frac{1}{\varepsilon_r}\right)} \text{ siemens per meter}$$

The radius lies between those of the other methods, i.e., $a < a' < b$. So, the diameter of the equivalent wire lies between the diameter of the conductor and the diameter of the insulation of the insulated wire. Distributed inductance and metal conductivity are less than in the other methods. The adjustments to wire diameter, loading and conductivity depend only on geometry and are frequency independent. The K6OIK method is based on electromagnetic theory. Its adjustments are exact in the quasistatic case, i.e. at frequencies for which the diameter is very small compared to a wavelength assuming the wire is in vacuum or air. **Table A** shows examples of equivalent wires for some common copper wire sizes and types. The conductivity of copper is assumed to be 58 MS/m (mega-siemens per meter).

The author's method also handles wires that have several layers of insulation made of different materials, and the materials are not restricted to just dielectrics. The extended formulas and their derivations are presented below.

Derivation of the K6OIK Formulas

In his treatment of thin dielectric cover, J.H. Richmond introduced the P function for a single layer of concentric dielectric cover

$$P = \left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$$

where a is the conductor radius, b is the insulation radius, and ε_r is the insulation dielectric constant. The P function is a dimensionless quantity that appears in the equations that define a bare wire equivalent to an insulated wire. For a distributed line charge q coulombs per meter, the electric flux density is directed radially outward and depends only on distance from the central axis

$$D_\rho = \frac{q}{2\pi\rho}$$

By electromagnetic boundary conditions, the normal component of **D** is unaltered at boundaries (by Gauss's law). Accordingly, for concentric cylindrical dielectric layers under an electrostatic assumption, this formula is correct at all interfaces and throughout space. For concentric cylindrical dielectric layers, the electric field **E** is radially directed, and its value depends on medium according to

$$E_\rho = \frac{1}{\varepsilon_r\varepsilon_0}D_\rho$$

Table A. Some Common Equivalent Wires by K6OIK Method.

	Solid / PVC			*Stranded / Polyethylene*		
AWG	14	12	10	14	12	10
Inner diameter, mm	1.6	2.1	2.6	1.9	2.4	2.9
Outer diameter, mm	3.4	3.9	4.5	2.4	2.9	3.4
Dielectric constant	3.6	3.6	3.6	2.26	2.26	2.26
Dielectric loss tangent	0.05	0.05	0.05	0.0002	0.0002	0.0002
Equivalent diameter, mm	2.758	3.284	3.864	2.164	2.667	3.169
Distributed inductance, nH/m	108.88	89.42	79.24	26.05	21.10	17.74
Conductivity, MS/m	19.52	23.72	26.26	44.70	46.97	48.57

The electric potential between cylindrical surfaces at $\rho = a$ and $\rho = b$ is

$$V = -\int_a^b E_\rho \, d\rho$$
$$= \frac{-q}{2\pi \varepsilon_r \varepsilon_0} \int_a^b \frac{1}{\rho} d\rho$$
$$= \frac{-q}{2\pi \varepsilon_r \varepsilon_0} \ln\left(\frac{b}{a}\right)$$

Distributed capacitance is

$$C = \frac{q}{V} = 2\pi \varepsilon_r \varepsilon_0 \ln\left(\frac{b}{a}\right) \text{ farads per meter}$$

For a bare wire of radius a' and dielectric constant $\varepsilon_r = 1$, we have

$$C' = 2\pi\varepsilon_0 \ln\left(\frac{b}{a'}\right) \text{ farads per meter}$$

Equating C' and C and solving for a' gives

$$\ln\left(\frac{a'}{a}\right) = \left(1 - \frac{1}{\varepsilon_r}\right) \ln\left(\frac{b}{a}\right) = P$$

The equivalent wire's radius is therefore

$$a' = a\left(\frac{b}{a}\right)^{\left(1-\frac{1}{\varepsilon_r}\right)} = a\,e^P$$

This formula was stated by A.G. Boswell, G3NOQ, **[58]**.

As the next step, the inductance of the equivalent bare wire of radius a' must be loaded to equal that of the insulated wire of radius a. The inductance can be determined from elementary magnetostatics. Consider a current filament I on the z axis. This current creates a magnetic field intensity vector **H**. By Ampère's circuital law, the azimuthal component of **H** varies inversely with distance ρ from the z axis.

$$H_\phi = \frac{I}{2\pi\rho}$$

Suppose a concentric cylinder with inner radius a and outer radius b are made of material having permeability μ_r and this cylinder in turn is surrounded by another cylinder of large radius $c >> b$ filled with vacuum or air. We may visualize this configuration as a coaxial cable with two layers of different dielectric materials. The magnetic flux density **B** is then given by

$$B_\phi = \begin{cases} \dfrac{\mu_r \mu_0 I}{2\pi\rho} & \text{for } a < \rho < b \\ \dfrac{\mu_0 I}{2\pi\rho} & \text{for } b < \rho < c \end{cases}$$

By Ampère's circuital law, the total flux passing azimuthally through a rectangular radial plane having boundaries $0 < z < l$, $a < \rho < c$ is the integral

$$\Phi = \iint_S \mathbf{B} \bullet \mathbf{n} \, dS = \int_0^l \int_a^c B_\phi \, d\rho \, dz$$
$$= \frac{\mu_0 I}{2\pi} \int_0^l \left(\int_a^b B_\phi \, d\rho + \int_b^c B_\phi \, d\rho \right) dz$$
$$= \frac{\mu_0 I l}{2\pi} \left(\mu_r \int_a^b \frac{1}{\rho} d\rho + \int_b^c \frac{1}{\rho} d\rho \right)$$
$$= \frac{\mu_r \mu_0 I l}{2\pi} \ln\left(\frac{b}{a}\right) + \frac{\mu_0 I l}{2\pi} \ln\left(\frac{c}{b}\right)$$

The distributed inductance (per unit length) of the wire of length l is then

$$L = \frac{\Phi}{I l}$$
$$= \frac{\mu_0}{2\pi} \left[\mu_r \ln\left(\frac{b}{a}\right) + \ln\left(\frac{c}{b}\right) \right]$$

If radius a is changed to a', the distributed inductance L is changed to L' where

$$L' = \frac{\mu_0}{2\pi} \left[\mu_r \ln\left(\frac{b}{a'}\right) + \ln\left(\frac{c}{b}\right) \right]$$

The change in inductance is given by

$$\Delta L = L' - L = \frac{\mu_r \mu_0}{2\pi} \ln\left(\frac{a}{a'}\right) \text{ henries per meter}$$

The change is negative if $a' > a$. In other words, as the conductor becomes fatter, its distributed inductance decreases. For nonmagnetic dielectric insulation material, $\mu_r = 1$. Consequently, to make the inductance of the equivalent bare wire the same as that of the insulated wire, we must load the equivalent wire with a positive distributed inductance equal to

$$-\Delta L = \frac{\mu_0}{2\pi} \ln\left(\frac{a'}{a}\right) = \frac{\mu_0}{2\pi} \left(1 - \frac{1}{\varepsilon_r}\right) \ln\left(\frac{b}{a}\right) = \frac{\mu_0 P}{2\pi} \text{ henries per meter}$$

Up to this point we have assumed PEC (infinite conductivity) wire. For wires of finite conductivity, we must set the bare wire conductivity to a smaller value in order that the equivalent bare wire of radius a' and the insulated wire of radius a have equal ac resistances. Skin depth δ is given by

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

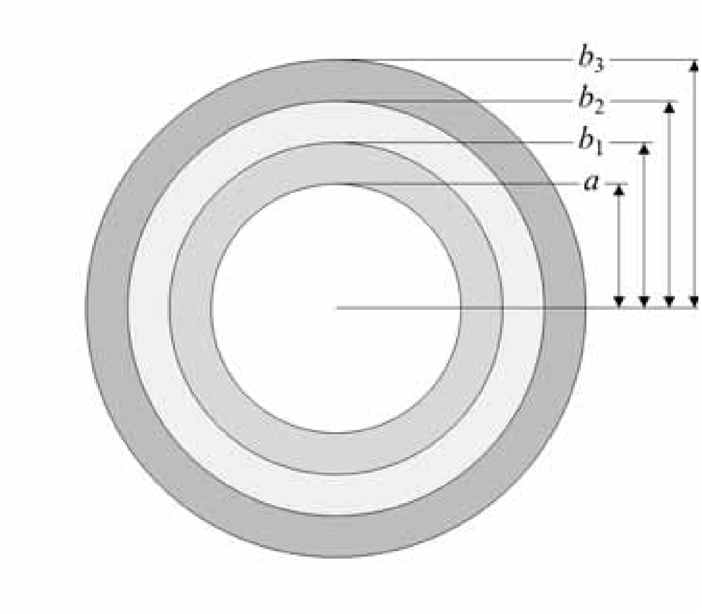

Figure 2 – Cross-section geometry of a multi-layer covered wire.

At low frequencies, there is no skin effect. A wire's ac resistance is the same as its dc resistance, inversely proportional to its cross-sectional area. At high (RF) frequencies, where skin depth δ is small compared to wire radius, a wire's distributed ac resistance is inversely proportional to its circumference.

Low frequencies: $R_{ac}(a) = \dfrac{1}{\pi a^2 \sigma}$ ohms per meter

High frequencies: $R_{ac}(a) = \dfrac{1}{2\pi a \delta \sigma} = \sqrt{\dfrac{\mu_0 f}{4\pi a^2 \sigma}}$ ohms per meter

In both cases, distributed ac resistance depends on the product $a^2\sigma$. The conductivity of an equivalent wire should be scaled to keep its ac resistance equal to that of the insulated wire. We therefore have, regardless of frequency regime,

$$\sigma' = \sigma \left(\frac{a}{a'}\right)^2 = \sigma \left(\frac{a}{b}\right)^{2\left(1-\frac{1}{\varepsilon_r}\right)} = \sigma e^{-2P} \quad \text{siemens per meter}$$

In addition to copper loss in the wire, there can be loss in the insulation materials. Such loss is ignored in the present treatment.

Multi-Layer Dielectric Coating

The K6OIK method can be generalized to multi-layer, lossless non-conductive dielectric cover, i.e., materials for which $\varepsilon_r \geq 1$, $\mu_r = 1$, $\sigma_{cover} = 0$. **Figure 2** shows the geometry of a multi-layer covered wire. The wire has an inner conductor of radius a surrounded by n concentric dielectric layers having outer radii $b_1 < b_2 < \ldots < b_n$. Each layer may have a different dielectric constant. For n layers, J.H. Richmond's P function is the dimensionless quantity given by

$$P = \left(1 - \frac{1}{\varepsilon_{r,1}}\right) \ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n} \left(1 - \frac{1}{\varepsilon_{r,i}}\right) \ln\left(\frac{b_i}{b_{i-1}}\right)$$

Let the wire have a distributed line charge of q coulombs per meter. The electric flux density **D** is radially directed.

$$D_\rho = \frac{q}{2\pi\rho}$$

The electric field **E** is likewise radially directed. At distance ρ off axis it is

$$E_\rho = \frac{1}{\varepsilon_0 \varepsilon_r} D_\rho = \frac{q}{2\pi \varepsilon_0 \varepsilon_r \rho}$$

The electric potential between cylindrical surfaces at $\rho = a$ and $\rho = b_n$ is

$$V = -\int_a^{b_n} E_\rho \, d\rho = \frac{-q}{2\pi\varepsilon_0} \int_a^{b_n} \frac{1}{\varepsilon_r(\rho)\rho} d\rho$$

$$= \frac{-q}{2\pi\varepsilon_0} \left[\frac{1}{\varepsilon_{r,1}} \ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n} \frac{1}{\varepsilon_{r,i}} \ln\left(\frac{b_i}{b_{i-1}}\right) \right]$$

Distributed capacitance is

$$C = \frac{q}{V} = \frac{-2\pi\varepsilon_0}{\left[\frac{1}{\varepsilon_{r,1}} \ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n} \frac{1}{\varepsilon_{r,i}} \ln\left(\frac{b_i}{b_{i-1}}\right) \right]}$$

For a bare wire of radius a' and all dielectric constants unity, $\varepsilon_{r,i} = 1$, we have

$$C' = \frac{-2\pi\varepsilon_0}{\left[\ln\left(\frac{b_1}{a'}\right) + \sum_{i=2}^{n} \ln\left(\frac{b_i}{b_{i-1}}\right) \right]} = \frac{-2\pi\varepsilon_0}{\ln\left(\frac{b_n}{a'}\right)}$$

Equating C' and C gives

$$\ln\left(\frac{a'}{a}\right) = \left(1 - \frac{1}{\varepsilon_{r,1}}\right) \ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n} \left(1 - \frac{1}{\varepsilon_{r,i}}\right) \ln\left(\frac{b_i}{b_{i-1}}\right) = P$$

Solving for a' gives the equivalent wire's radius as

$$a' = a \left(\frac{b_1}{a}\right)^{\left(1-\frac{1}{\varepsilon_{r,1}}\right)} \prod_{i=2}^{n} \left(\frac{b_i}{b_{i-1}}\right)^{\left(1-\frac{1}{\varepsilon_{r,i}}\right)} = a e^P$$

In order to make the self-inductance of the equivalent bare wire the same as that of the multi-layer insulated wire, we must load the equivalent wire with a positive distributed inductance equal to

$$-\Delta L = \frac{\mu_0}{2\pi} \ln\left(\frac{a'}{a}\right) = \frac{\mu_0}{2\pi} \left[\left(1 - \frac{1}{\varepsilon_{r,1}}\right) \ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n} \left(1 - \frac{1}{\varepsilon_{r,i}}\right) \ln\left(\frac{b_i}{b_{i-1}}\right) \right] = \frac{\mu_0 P}{2\pi} \quad \text{henries per meter}$$

The equivalent wire's conductivity must be scaled inversely with its effective radius according to

$$\sigma' = \sigma \left(\frac{a}{a'}\right)^2 = \sigma \left(\frac{a}{b_1}\right)^{2\left(1-\frac{1}{\varepsilon_{r,1}}\right)} \prod_{i=2}^{n} \left(\frac{b_{i-1}}{b_i}\right)^{2\left(1-\frac{1}{\varepsilon_{r,i}}\right)} = \sigma e^{-2P} \quad \text{siemens per mete}$$

Multi-Layer Magnetic Coating

The K6OIK method can be generalized to lossless, non-conductive magnetic cover, i.e., materials for which $\varepsilon_r = 1$, $\mu_r \geq 1$, $\sigma_{cover} = 0$. An example is ferrite-coated wire. For magnetic cover, Lee and Balmain**[27]** define a Q function analogous to Richmond's P function, which for single-layer cover is

$$Q = (\mu_r - 1)\ln\left(\frac{b}{a}\right)$$

and for n layers is

$$Q = (\mu_{r,1} - 1)\ln\left(\frac{b_1}{a}\right) + \sum_{i=2}^{n}(\mu_{r,i} - 1)\ln\left(\frac{b_i}{b_{i-1}}\right)$$

Q like P is dimensionless. Q appears in the distributed inductance analysis below.

Because all layer dielectric constants are unity, the radius of a bare wire equivalent to one with n-layered magnetic cover is unchanged

$$a' = a$$

Inductance is found by analysis similar to that for the multi-layer dielectric case, the inductance per unit length of the wire with n-layered magnetic cover of length l is

$$L = \frac{\mu_0\,\mu_{r,1}}{2\pi}\ln\left(\frac{b_1}{a}\right) + \frac{\mu_0}{2\pi}\left[\sum_{i=2}^{n}\mu_{r,i}\ln\left(\frac{b_i}{b_{i-1}}\right)\right] + \frac{\mu_0}{2\pi}\ln\left(\frac{c}{b_n}\right)$$

If all relative permeabilities are changed to unity, the inductance L is changed to L' where

$$L' = \frac{\mu_0}{2\pi}\ln\left(\frac{b_1}{a}\right) + \frac{\mu_0}{2\pi}\left[\sum_{i=2}^{n}\ln\left(\frac{b_i}{b_{i-1}}\right)\right] + \frac{\mu_0}{2\pi}\ln\left(\frac{c}{b_n}\right)$$

The difference or delta inductance is given by

$$\Delta L = L' - L = \frac{\mu_0}{2\pi}(1-\mu_{r,1})\ln\left(\frac{b_1}{a}\right) + \frac{\mu_0}{2\pi}\left[\sum_{i=2}^{n}(1-\mu_{r,i})\ln\left(\frac{b_i}{b_{i-1}}\right)\right] = -\frac{\mu_0 Q}{2\pi}$$

To make the self-inductance of the equivalent bare wire the same as that of the multi-layer magnetic covered wire, we must load the equivalent wire with a positive distributed inductance equal to

$$-\Delta L = \frac{\mu_0}{2\pi}(\mu_{r,1}-1)\ln\left(\frac{b_1}{a}\right) + \frac{\mu_0}{2\pi}\left[\sum_{i=2}^{n}(\mu_{r,i}-1)\ln\left(\frac{b_i}{b_{i-1}}\right)\right] = \frac{\mu_0 Q}{2\pi} \quad \text{henries per meter}$$

The effective conductivity of the equivalent bare wire requires no correction. Because the equivalent radius does not change for wires with magnetic cover, the ac resistance of the equivalent bare wire is the same as that of the original coated wire. Consequently $\sigma' = \sigma$.

Multi-Layer Magneto-Dielectric Coating

Finally, we consider a multi-layer cover of lossless, non-conductive magneto-dielectric materials for which each layer satisfies $\varepsilon_r \geq 1$, $\mu_r \geq 1$, $\sigma_{cover} = 0$. An example is a ferrite coated wire covered by a plastic sheath. We merely need to apply the results of the dielectric and magnetic cases treated above simultaneously.

The magnetic layer correction is via a loading adjustment. Thin magnetic layers do not increase effective radius but do add series inductance loading. Dielectric layers by contrast increase effective radius, reduce effective conductance, and add a small series inductance load correction.

Using the notations introduced above, a bare wire is equivalent to one that has n concentric layers of thin magneto-dielectric cover provided the radius, conductivity, and distributed inductance loading are

$$a' = a\,e^{P}$$

$$\sigma' = \sigma\,e^{-2P}$$

$$-\Delta L = \frac{\mu_0}{2\pi}(P+Q)$$

The distributed inductance load is the sum of two terms. The first term corrects for the change in conductor radius. The second term corrects for the magnetic relative permeabilities of the layers.

Further generalizations are possible to account for electric and magnetic loss tangents, which the present analysis has not considered. The results here should handle many wire types that an antenna modeler may encounter.

Table B. Equivalent Wire Models for Single-Layer Insulated Wire.

Parameter	*W4RNL*	*RA9MB*	*K6OIK*
Radius	a	b	$a\left(\frac{b}{a}\right)^{\left(1-\frac{1}{\varepsilon_r}\right)}$
Distributed Inductance Load, H/m	$\frac{\mu_0}{2\pi}\left(\frac{b}{a}\varepsilon_r\right)^{\frac{1}{12}}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$	$\frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r k_{abs}^2}\right)\ln\left(\frac{b}{a}\right)$	$\frac{\mu_0}{2\pi}\left(1-\frac{1}{\varepsilon_r}\right)\ln\left(\frac{b}{a}\right)$
Conductivity, S/m	σ	σ	$\sigma\left(\frac{a}{b}\right)^{2\left(1-\frac{1}{\varepsilon_r}\right)}$
Accuracy	Good	Better	Best
Insulation	Dielectric	Dielectric	General
Used in	*4nec2*	*MMANA*	*EZNEC*, *SimNEC*

Materials Restrictions

The accuracy of the analysis above depends on assumptions about materials and geometry. The central conductor is the only material that conducts and is nonmagnetic metal. The cover materials are assumed to be non-conducting and lossless. Electric and magnetic loss tangents are assumed to be zero. The cover materials are electromagnetically simple, i.e., constant, linear, homogeneous, and isotropic. Exotic materials that are either time-varying, nonlinear, bilinear, inhomogeneous, or anisotropic are specifically ruled out. Ferrites in homogenized form (e.g., ceramics) are allowed. Ferrites in crystal form are anisotropic and violate our assumptions. For many materials, electromagnetic parameters are a function of frequency. This fact does not matter because we consider only the single-frequency sinusoidal steady-state (also called the "time-harmonic" or "monochromatic") case. For most materials, dielectric constant and magnetic permeability depend on frequency and temperature. The values used in examples here are merely typical. The electromagnetic behavior of matter and materials is discussed in C.A. Balanis **[78]** and A. Zangwill **[83]** and in specialized texts in chemistry and physics.

The modeling methods are limited to insulation layers that are electrically thin. The thickness of the cover must be small compared to a wavelength in the medium of the insulation.

$$b - a \ll \lambda = \frac{c}{f\sqrt{\varepsilon_r \mu_r}}$$

When this condition is not met or when a dielectric has arbitrary shape and dimensions, different methods of analysis can be used. The internal fields in a dielectric resonator antenna (DRA) are cavity modes. The cavity modes couple to and drive the external field. One common shape for dielectric radiators is the cylinder. Radiation from a cylindrical resonator is generally either axial mode or normal mode. Fat cylinders can radiate in the axial mode, in which radiation is end-fire, in the direction of the axis. The cylinder acts like a waveguide or traveling wave structure. An example is a polyrod antenna. By contrast, thin cylinders generally radiate in the normal mode, so called because radiation is sideways, normal, or perpendicular to the cylinder's axis. Some examples include dipoles and monopoles, "flexible antennas for portable radios ("rubber duck" antennas)," and even tall trees.

Our analysis is for wires that can be treated as long concentric cylinders. End effects of finite length cylinders are ignored. One should not expect our analysis to correctly model short ferrite beads snug on a wire. An assessment of the theoretical soundness of quasistatic approaches to electrically thin cover materials was given by A.I. Mowete, et al., **[75]**, **[76]**, **[77]**. Techniques to model general dielectric objects by using thin-wire antenna modeling programs are reviewed in **[89]**.

Summary of Methods

All of the methods assume the insulation is electrically thin. As insulation thickness is made greater, all methods become inaccurate, but the *NEC-4.2* IS function should work accurately for a greater range of b/a ratios. The K6OIK and Richmond methods are similar in goal but different in technique. Both treat insulation as a perturbation. The difference is Richmond treats the perturbation as an additive correction to the MoM impedance matrix. K6OIK, on the other hand, treats the perturbation as a small change in effective diameter. Neither approach increases the self-inductance of segments or wires. Rather, K6OIK keeps the inductance of equivalent wires constant by adding exactly enough inductance to compensate for the smaller self-inductance of larger diameter wires. Similarly, wire conductivity is reduced exactly enough to compensate for the smaller ac resistance of larger diameter wires. Both the Richmond and K6OIK perturbations affect the entire MoM impedance matrix. They do more than just diagonally load the matrix. The IS feature of *NEC-4.2* is the most accurate method among those under discussion and the only one that has been validated extensively against measured measured data. However, the K6OIK method achieves the same result without directly modifying the impedance matrix. Moreover, the K6OIK method is the only method that allows multiple layer insulations and insulation materials that can be dielectric, magnetic, and magneto-dielectric — a degree of generality that the *NEC-4.2* IS function lacks.

"Equivalent wire" methods (W4RNL, RA9MB, and K6OIK) presume the MoM impedance matrix is unavailable for direct modification. Accordingly, these methods can at best modify the MoM impedance matrix indirectly, by modifying the geometry, loading, and metal conductivity, of the wires. However, wire lengths must be kept constant to keep from breaking a model. Wire diameters and distributed loading (e.g., inductance and wire loss due to finite conductivity) are the only variables that may be adjusted given that the impedance matrix is not available for direct modification or the addition of correction terms. **Table B** summarizes the three methods of modeling single-layer insulated wire. The methods can be used with any thin-wire program. W4RNL's method is built into *4nec2*. RA9MB's method is built into *MMANA*. K6OIK's dielectric single-layer method has been added to *EZNEC* v7.0.3 and *SimNEC*.

The following differences are noted. The W4RNL method defines equivalent wires by adding distributed inductance alone.

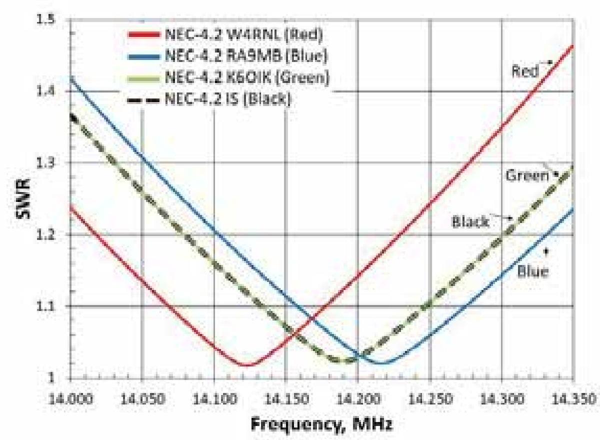

Figure 3 – Comparison of four insulated wire methods on a 20-meter square loop. Data from AC6LA.

Table C. Equivalent Wire Models for n-Layer Covered Wire.

Parameter	*Dielectric Cover (P > 0, Q = 0)*	*Magnetic Cover (P = 0, Q > 0)*	*Magneto-Dielectric Cover (P > 0, Q > 0)*
Radius	$a\,e^{P}$	a	$a\,e^{P}$
Distributed Inductance Load, H/m	$\frac{\mu_0}{2\pi}P$	$\frac{\mu_0}{2\pi}Q$	$\frac{\mu_0}{2\pi}(P+Q)$
Conductivity, S/m	$\sigma\,e^{-2P}$	σ	$\sigma\,e^{-2P}$

Conductor diameter and metal conductivity are not changed. The RA9MB method defines equivalent wires by adding distributed inductance and increasing the conductor diameter to that of the insulation, but adjustment to metal conductivity to account for increased diameter is absent. Additionally. the method has an undetermined parameter. The K6OIK method defines equivalent wires by (1) increasing the conductor diameter to a value between the diameter of the conductor and the diameter of the insulation, (2) adding distributed inductance, (3) reducing the metal conductivity. This three-part correction gives the equivalent wire the same distributed capacitance, inductance, and loss as the original insulated wire. This method, based on electromagnetic quasistatic theory, expresses the parameters of equivalent wires in terms of physical constants and geometric dimensions with no undetermined variables.

The K6OIK method handles complicated covers such as multi-layered insulations or wires covered by magneto-dielectric materials. **Table C** summarizes the parameters for bare wires that are equivalent to various multi-layered lossless insulations. Parameter definitions and derivations are above. The K6OIK single-layer formulas in Table B are a special case of the *n*-layer formulas in Table C. The reader is referred to the works of J.H. Richmond **[20]**, **[21]**, E.H. Newman **[23]**, J.P.Y. Lee, and K.G. Balmain **[27]**, and J. Moore, and M.A. West **[43]** for theoretical discussion.

Accuracy Assessment and Validation

An antenna made of insulated wire will behave differently from one made of bare wire. The differences show up in current distribution, radiation pattern, field strength, efficiency, feed point impedance, and resonant frequency. Amateur antenna builders are generally most interested in impedance, resonant frequency and SWR. Dielectric insulation mainly affects the feed point reactance, more so than the resistance of a wire antenna. The effect is to increase the reactance by a small increment. When viewed on a Smith chart, the antenna's impedance curve is shifted upward. Each impedance point shifts clockwise on its constant *r*-circle. Resonant frequencies are accordingly shifted down, and anti-resonant frequencies are shifted up. In frequency bands where the impedance curve is locally tangent to an *r*-circle, the shift has the same effect as frequency scaling, making the wire appear longer. This equivalence only holds near tangencies. Near resonance, adding insulation makes the wire appear longer. If the impedance curve near the resonance is approximately tangent to an *r*-circle on the Smith chart. The effect is to shift the resonant frequency down.

Richmond's method, which became the IS function in *NEC-3* and *NEC-4.2*, has been extensively validated against measured data. Accordingly, *NEC-4.2*'s IS function is the gold standard against which other computational methods for modeling single-layer dielectric insulation should be evaluated and compared. However, *n*-layer and magneto-dielectric insulations are beyond even its capability. The K6OIK method is the only one of the methods presented above that can handle multi-layer insulations.

We compared the various methods on four insulated-wire antenna models. Test models were run to compare different combinations of insulation method and thin-wire engine, specifically *NEC-4.2* and *NEC-5* **[91]**. We present results for four example models. The first example is a 20-meter band, full-wavelength, insulated square loop for which *NEC-4.2*'s IS command was compared to the W4RNL, RA9MB, K6OIK equivalent wire methods. The second and third examples use the same models that were used by G.J. Burke to validate the NEC IS command. IS is compared to the K6OIK method and original measured test data **[23]**, **[34]**. The final example has a more difficult model, an insulated isosceles delta loop devised by AC6LA. This example compares *NEC-5* using the K6OIK method to NEC-4.2's IS command.

Example 1 compares three different equivalent wire methods against the IS feature of *NEC-4.2* on a 20-meter band, full-wavelength, square loop antenna. The antenna wire is 2-mm diameter copper wire insulated with a 0.6-mm thick PVC insulation having dielectric constant 3.5. **Figure 3** shows the results. The graph shows the SWR computed for a reference impedance of 120 Ω. *NEC-4.2* IS (black dashed curve) puts the SWR minimum at 14.190 MHz. The W4RNL method (red curve) puts the SWR minimum 67 kHz too low. The RA9MB method (blue curve) puts it 26 kHz too high. Only the K6OIK method (green curve) agrees spot on with the *NEC-4.2* IS calculation.

Table D. UHF Insulated Dipole Parameters.

Length	8 inches
Length to radius ratio	640
Conductor	Copper
Insulation b/a	5.84
Dielectric constant	2.3
Resonant frequency	~ 600 MHz
Frequency sweep	0 to 1.2 GHz

Table E. UHF Insulated Square Loop Parameters.

Perimeter	8 inches
Perimeter to radius ratio	640
Conductor	Copper
Insulation b/a	5.84
Dielectric constant	2.3
Resonant frequency	~ 1.2 GHz
Frequency sweep	0 to 2.4 GHz

In his original validation of the NEC IS command, G.J. Burke did a three-way comparison of Richmond, NEC IS, and laboratory measured test data. The comparison was presented as graphs of admittance $Y = G + jB$, **[34]**. The predicted feed point admittance was compared to measured data. The test data was measured at The Ohio State University (OSU), **[23]**, **[34]**. Also, the computed radiation efficiency was compared to theory. The author repeated two of Burke's test cases: a UHF insulated dipole and a UHF insulated full-wave square loop.

Example 2 is Burke's UHF insulated dipole. The insulated wire was RG-59 coax with outer jacket and braid removed, leaving a dielectric covered copper center conductor. Dielectric loss tangent was assumed to be zero. The antenna was frequency swept from dc to twice the resonant frequency. **Table D** gives the dipole's physical and geometrical parameters.

Figures 4 and **5** show the feed point admittance (conductance and susceptance) of the insulated dipole. It is observed that the agreement between the K6OIK equivalent wire method and *NEC-4.2* IS is near exact. It is observed that both computational methods have good agreement with the OSU measured data. This example was one of several that Burke used to validate the IS feature of NEC.

Example 3 is Burke's UHF insulated full-wave square loop. **Table E** lists the loop's physical and geometrical parameters. Like the insulated dipole, the square loop's insulated wire was RG-59 coax with outer jacket and braid removed, leaving a dielectric covered copper center conductor. Dielectric loss tangent was assumed to be zero. The antenna was frequency swept from dc to twice the resonant frequency.

Figures 6 and **7** show the admittance (conductance and susceptance) of the insulated full-wavelength square loop. It is observed again that the K6OIK equivalent wire method's agreement with *NEC-4.2* IS is near exact. The agreement between both computational methods and the OSU measured data is not as good as for the insulated dipole. The reason is unknown. It is possible that the model parameters in Table E were not stated with enough precision. A small error in the insulation diameter or dielectric constant is a possibility. It should also be noted that the OSU measurements were made at a time before anechoic antenna test chambers and precise measurement test protocols were in wide use. Proper calibration of test setup, especially "de-embedding" a device under test (DUT) from any stray capacitance and parasitic inductance of the text setup is important for obtaining accurate measurement results. Parasitic capacitance or inductance in the test setup may

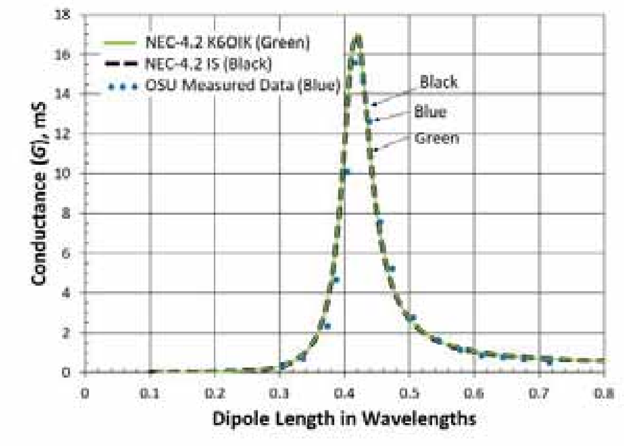

Figure 4 – *NEC-4.2* calculated conductance of test dipole, comparing IS and K6OIK methods. Measured test data is from The Ohio State University.

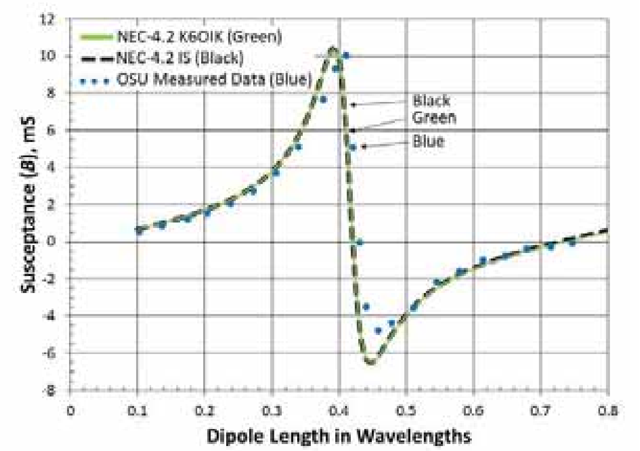

Figure 5 – *NEC-4.2* calculated susceptance of test dipole, comparing IS and K6OIK methods. Measured test data is from The Ohio State University.

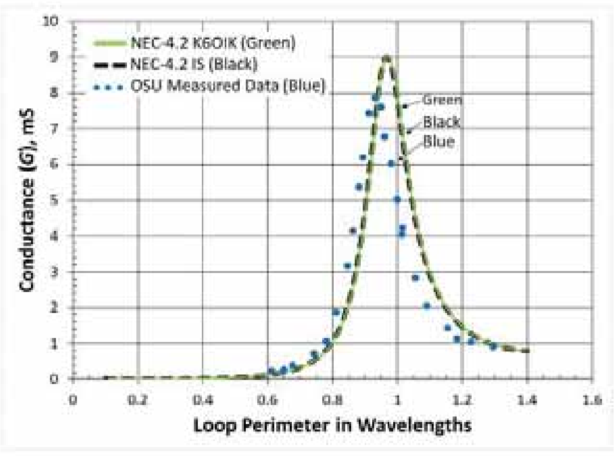

Figure 6 – *NEC-4.2* calculated conductance of test square loop, comparing IS and K6OIK methods. Measured test data is from The Ohio State University.

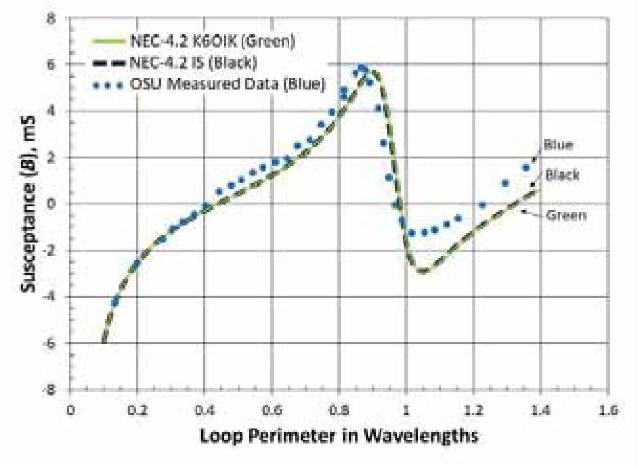

Figure 7 – *NEC-4.2* calculated susceptance of test square loop, comparing IS and K6OIK methods. Measured test data is from The Ohio State University.

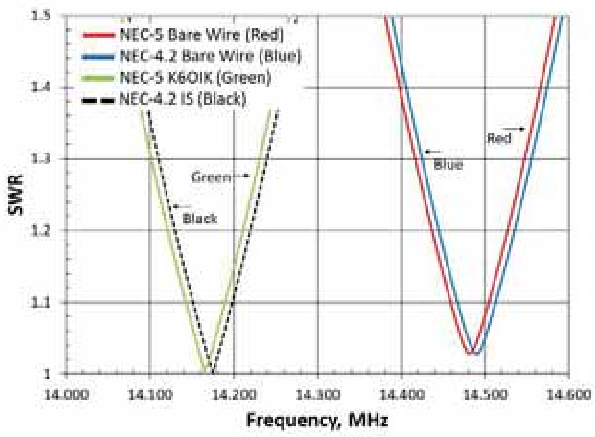

Figure 8 – SWR shift due to insulation of two methods with NEC-5 and NEC-4.2. Data from AC6LA.

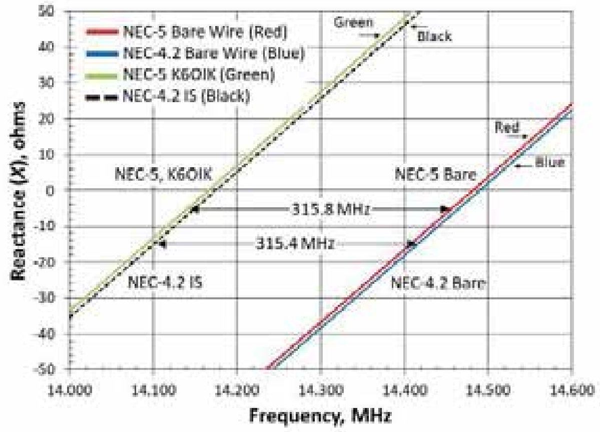

Figure 9 – Reactance shift due to insulation of two methods with NEC-5 and NEC-4.2. Data from AC6LA.

account for the apparent shift in resonant frequency. Nowadays, at UHF and microwave frequencies, modeling and computation are considered to be more accurate than physical measurement unless the measurements are made very carefully.

Example 4 is our last example—an HF bottom-fed isosceles delta loop. AC6LA devised this model as a challenging validation test to compare *NEC-5* using the K6OIK method against *NEC-4.2* using its internal IS function. The antenna is made of the same insulated wire as the square loop in Example 1 and dimensioned for 50 Ω impedance at 14.175 MHz.

When comparing different combinations of insulation method and engine, it is important to realize that different engines give different impedances for the same bare wire model. In order to isolate the effect of an insulation method from the native error in an engine, one should compare the impedance delta between bare and insulated wire models. The delta that matters most is in the frequency shift of the feed point reactance $\Delta X(f)$. The shift in feed point resistance $\Delta R(f)$ is very small. By comparing deltas instead of total impedance, we avoid confusing an engine's inaccuracy with the insulation method's inaccuracy.

Figure 8 shows results for NEC-5 using the K6OIK method versus *NEC-4.2*'s IS command. The data shows the SWR shifts between bare and insulated wire predicted by two methods using different engines. The graph gives comparisons both of *NEC-5* versus *NEC-4.2*, as well as K6OIK versus IS. The red and blue traces are for bare wire, and the green and black dashed traces are for PVC insulated wire. Regarding *NEC-5* versus *NEC-4.2*, an 8-kHz difference is observed between the two engines for identical bare-wire antenna models absent insulation. This difference is due to errors that are native to the engines.

Figure 9 shows the reactance shift between bare and insulated wire predicted by two methods using two engines. Over the narrow bandwidth the reactance curves are straight lines. Each reactance curve's resonant frequency (zero crossing) was calculated from its slope and intercept found by linear regression analysis.

Table F shows the resonant frequencies for the various combinations of engine and insulation method. The 8-kHz difference between the *NEC-5* and *NEC-4.2* engines is again seen. Regarding K6OIK versus IS, the bare-to-insulated shifts of reactance are almost identical: 315.8 kHz for *NEC-5* using K6OIK versus 315.4 kHz for *NEC-4.2* IS. The 400-Hz difference between insulation methods (K6OIK versus IS) is 20 times less than the 8-kHz native difference between the *NEC-4.2* and *NEC-5* engines observed in Figures 8 and 9. We conclude the K6OIK method under *NEC-5* produces the same insulation frequency offset as the IS command of *NEC-4.2*.

Modeling of multi-layer magneto-dielectric sheaths is beyond the capability of the IS feature in *NEC-4.2* and indeed all commercial thin-wire electromagnetic modeling software. Consequently, the K6OIK multi-layer formulas cannot be compared to commercial thin-wire software because none exist. However, modern computational electromagnetics (CEM) software based on surface equivalence or volume equivalence principles can be used, as can finite-element method (FEM) programs such as ANSYS *HFSS*. Validation against measured test data remains to be performed.

Conclusion

Techniques for modeling insulated wire were reviewed and explained. We considered insulations made of layers of dielectric, magnetic, and magneto-dielectric materials. Only lossless materials (loss tangent zero) were considered. A sequel may examine losses in linear low-loss dielectric and magnetic materials and give methods for determining antenna radiation efficiency and gain pattern. To the author's knowledge the formulas presented are new and have not been published before. These formulas enable an antenna modeler to model wires coated by many materials. The results here should handle many wire types that an antenna modeler may encounter.

Table F. Resonant Frequencies in MHz.

Bare Wire		*Insulated Wire*	
NEC-4.2	NEC-5	NEC-4.2 IS	NEC-5 and K6OIK
14.48980	14.48165	14.17439	14.16582

Acknowledgment

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Bibliography and References (in chronological order)

1. F. Harms, "Elektromagnetische Wellen an einem Draht mit isolierender zylindrischer Hülle," *Annalen der Physik* (in German), vol. 328, no. 6, pp. 44-60, May 1907.
2. A.A. Pistolkors, "The Radiation Resistance of Beam Antennas," *Proceedings of the IRE*, vol. 17, no. 3, pp. 562-579, Mar. 1929.
3. P.S. Carter, "Circuit Relations in Radiating Systems and Applications to Antenna Problems," *Proceedings of the IRE*, vol. 20, no. 6, pp. 1004-1041, June 1932.
4. G. Goubau, *Theory of Surface Waves and Their Application to Transmission Lines*, Signal Corps Engineering Laboratories, 1950.
5. G. Goubau, "Single-Conductor Surface-Wave Transmission Lines," *Proceedings of IRE*, vol. 39, no. 6, pp. 619-624, June 1951.
6. T.E. Roberts, Jr., "Theory of the Single-Wire Transmission Line," *J. Applied Physics*, vol. 24, no. 1, pp. 57-67, Jan. 1953.
7. T.E. Roberts, Jr., "An Experimental Investigation of the Single-Wire Transmission Line," *IRE Transactions on Antennas and Propagation*, vol. 2, no. 2, pp. 46-56, Apr. 1954.
8. G. Goubau, "Designing Surface-Wave Transmission Lines," *Electronics*, pp. 180-184, Apr. 1954.
9. T.T. Wu, "Theory of the Dipole Antenna and the Two-Wire Transmission Line," *Journal of Mathematical Physics*, vol. 2, no. 4, pp. 550-574, July-Aug 1961.
10. L. W. Zelby, "Propagation Modes on a Dielectric Coated Wire," *Journal of The Franklin Institute*, vol. 274, no. 2, Aug. 1962.
11. K. Iizuka and R.W.P. King, "The Terminated Insulated Antenna in a Conducting Medium," *IEEE International Symposium on Antennas and Propagation*, vol. 1, pp. 196-198, Boulder, CO, July 9-11, 1963.
12. K. Iizuka, "An Experimental Study of the Insulated Dipole Antenna Immersed in a Conducting Medium," *IEEE Transactions on Antennas and Propagation*, vol. 11, no. 5, pp. 518-532, Sept. 1963.
13. R.W.P. King, "Theory of the Terminated Insulated Antenna in a Conducting Medium," *IEEE Transactions on Antennas and Propagation*, vol. 12, no. 3, pp. 305-318, May 1964.
14. D. Lamensdorf and C.Y. Ting, "Dielectric Coated Cylindrical Antenna," *IEEE International Symposium on Antennas and Propagation*, vol. 4, pp. 221-227, Palo Alto, CA, Dec. 5-7, 1966.
15. D. Lamensdorf, "An Experimental Investigation of Dielectric-Coated Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 15, no. 6, pp. 767-771, Nov. 1967.
16. C-Y. Ting, "Theoretical Study of Finite Dielectric-Coated Cylindrical Antenna," *Journal of Mathematical Physics*, vol. 10, no. 3, pp. 480-493, Mar. 1969.
17. J.C. Rogers and I.C. Peden, "The Electrically Short Sheathed Dipole: Experimental Relationship Between Measured Admittance and Permittivity of the External Medium, *IEEE International Symposium on Antennas and Propagation*, pp. 33-36, Williamsburg, VA, Dec. 11-14, 1972.
18. J.C. Rogers and I.C. Peden, "The Electrically Short Sheathed Dipole: Experimental Relationship Between Its Measured Admittance and the Permittivity of the External Medium," *IEEE Transactions on Antennas and Propagation*, vol. 21, no. 6, pp. 857-862, Nov. 1973.
19. R.W.P. King, K-M. Lee, S.R. Mishra, and G.S. Smith, "Insulated Linear Antenna: Theory and Experiment," *Journal of Mathematical Physics*, vol. 45, no. 4, pp. 1688-1697, Apr. 1974.
20. J.H. Richmond, *Radiation and Scattering by Thin-Wire Structures in the Complex Frequency Domain*, ElectroScience Laboratory, The Ohio State University, NASA CR-2396, May 1974.
21. J.H. Richmond, *Computer Program for Thin-Wire Structures in a Homogeneous Conducting Medium*, ElectroScience Laboratory, The Ohio State University, NASA CR-2399, June 1974.
22. R.W.P. King, K-M. Lee, G.S. Smith, and S.R. Mishra, "Insulated Linear Antenna: Theory and Experiment – II," *Journal of Applied Physics*, vol. 46, no. 3, pp. 1091-1098, Mar. 1975.
23. J.H. Richmond and E.H. Newman, "Dielectric Coated Wire Antennas," *Radio Science*, vol. 11, no. 1, pp. 13-20, Jan. 1976.
24. R.W.P. King, "The Many Faces of the Insulated Antenna," *Proceedings of IEEE*, vol. 64, no. 2, pp. 228-238, Feb. 1976.
25. M.S. Smith, "Properties of Dielectrically Loaded Antennas," *Proceedings of IEE*, vol. 124, no. 10, pp. 837-839, Oct. 1977.
26. J.R. James and A. Henderson, "Electrically Short Monopole Antennas with Dielectric or Ferrite Coatings," *Proceedings of IEE*, vol. 125, no. 9, pp. 793-803, Sept. 1978.
27. J.P.Y. Lee and K.G. Balmain, "Wire Antennas Coated with Magnetically and Electrically Lossy Material," *Radio Science*, vol. 14, no. 3, pp. 437-445, May-June 1979.
28. B.D. Popović, A.R. Djordjević, and N.M. Kirćanski, "Simple Method for Analysis of Dielectric-Coated Wire Antennas," *IERE The Radio and Electronic Engineer*, vol. 51, no. 3, pp. 141-145, Mar. 1981.
29. R.W.P. King, B.S. Trembly, and J.W. Strohbehn, "The Electromagnetic Field of an Insulated Antenna in a Conducting or Dielectric Medium," *IEEE Transactions on Microwave Theory and Techniques*, vol. 31, no. 7, pp. 574-583, July 1983.
30. B.D. Popović and A. Nešić, "Generalisation of the Concept of Equivalent Radius of Thin Cylindrical Antennas," *IEE Proceedings, Pt. H: Microwaves, Optics and Antennas*, vol. 131, no. 3, pp. 153-158, June 1984.
31. L.I. Parad, "Comparison of Two Theories for Buried Insulated Wire," *IEEE International Symposium on Antennas and Propagation*, pp. 97-100, Boston, MA, June 25-29, 1984.
32. J. Moore and A.C. Scrimgeour, *Wire Dipoles and Antennas with Dielectric or Magnetic Coatings*, AWRE Rept. 019/85, Atomic Weapons Research Establishment, U.K., 1985, ISBN 0855181702.
33. P.L. Huddleston, "Scattering from Conducting Finite Cylinders with Thin Coatings," *IEEE Transactions on Antennas and Propagation*, vol. 35, no. 10, pp. 1128-1136, Oct. 1987.
34. G.J. Burke, *A Model for Insulated Wires in the Method of Moments Code NEC*, UCID-21301, Lawrence Livermore National Laboratory, Jan. 1988.
35. P.L. Huddleston, "Scattering by Finite, Open Cylinders Using Approximate Boundary Conditions," *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 2, pp. 253-259, Feb. 1989.
36. B.P. Sinha and S.A. Saoudy, "Rigorous Analysis of Finite Length Insulated Antenna in Air," *IEEE Transactions on Antennas and Propagation*, vol. 38, no. 8, pp. 1253-1258, Aug. 1990.
37. J. Yamauchi and H. Nakano, "Hallen-Type Integral Equation to a System Composed of Wires with Dielectric Coating," *Electronics Letters*, vol. 26, no. 17, pp. 1412-1413, Aug. 16, 1990.
38. K.C. Chen and L.K. Warne, "A Uniformly Valid Loaded Antenna Theory," *IEEE Trans. Transactions on Antennas and Propagation*, vol. 40, no. 11, pp. 1313-1323, Nov. 1992.
39. R.P. Haviland, W4MB, "Insulated Antennas: The Effect of Insulating Coatings on Antennas," *Communications Quarterly*, premier issue, pp. 75-79, Nov. 1993.
40. A. Rubio Bretones, R. Gómez Martin, A. Salinas, and I. Sánchez, "Time Domain Analysis of Dielectric Coated Wire Antennas and Scatterers," *IEEE Mediterranean Electrotechnical Conference* (MELCON), pp. 1174-1176, Antalya, Turkey, Apr. 12-14, 1994.
41. A. Rubio Bretones, A. Salinas, R. Gómez Martín, and I. Sánchez García, "Time Domain Analysis of Dielectric-Coated Wire Antennas and Scatterers," *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 6, pp. 815-819, June 1994.
42. Ratajczak, P. Brachat, and J-L. Guiraud, "Rigorous Analysis of Three-Dimensional Structures Incorporating Dielectrics," *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 8, pp. 1077-1088, Aug. 1994.
43. J. Moore and M.A. West, "Simplified Analysis of Coated Wire Antennas and Scatterers," *IEE Proceedings – Microwave Antennas Propagation*, vol. 142, no. 1, pp. 14-18, Feb. 1995.
44. A. Rubio Bretones, R. Gómez Martín, and I. Sánchez García, "Time-Domain Analysis of Magnetic-Coated Wire Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 43, no. 6, pp. 591-596, June 1995.
45. S.A. Adekola and A.I. Mowete, "On the Problem of Dielectric-Coated Thin-Wire Antennas," *IEEE International Symposium Antennas and Propagation*, vol. 4, p. 1899 (abstract only), Newport Beach, CA, June 18-23, 1995.
46. C. Ozdemir and H. Ling, "Interpretation of Scattering Phenomenology in Dielectric-Coated Wire via Joint Time-Frequency Processing," *IEEE International Symposium Antennas and Propagation*, Baltimore, MD, July 21-26, 1996.

47. V.P. Kismereshkin and G.N. Lobova, “Simulation of a Linear Antenna Array On the Basis of a Single-Wire Transmission Line” (in Russian), *Pribory i Tekhnika Eksperimenta*, no. 5, pp. 85-86, Sept-Oct. 1996.
48. L. Richard, A.I. Nosich, and J.P. Daniel, “Surface-Impedance Model Analysis of a Coated Cylinder with Application to Wave Propagation and Conformal Antennas,” *IEE 10th International Conference on Antennas and Propagation (ICAP)*, conf. publ. no. 436, vol. 1, pp. 123-125, Edinburgh, UK, Apr.14-17, 1997.
49. C. Ozdemir and H. Ling, “Joint Time-Frequency Interpretation of Scattering Phenomenology in Dielectric-Coated Wires,” *IEEE Trans. Antennas and Propagation*, vol. 45, no. 8, pp. 1259-1264, Aug. 1997.
50. Z. Shen and R.H. MacPhie, “Input Admittance of a Multilayer Insulated Monopole Antenna,” *IEEE Transactions on Antennas and Propagation*, vol. 46, no. 11, pp. 1679-1686, Nov. 1998.
51. T.W. Hertel and G.S. Smith, “On the Accuracy of the Transmission Line Theory for the Insulated Linear Antenna,” *IEEE International Symposium on Antennas and Propagation*, pp. 768-771, Orlando, FL, July 11-16, 1999.
52. L. Richard, A.I. Nosich, and J-P. Daniel, “Revisiting the Waves on a Coated Cylinder by Using Surface-Impedance Model,” *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 8, pp. 1374-1375, Aug. 1999.
53. U. Jakobus, “Comparison of Different Techniques for the Treatment of Lossy Dielectric/Magnetic Bodies within the Method of Moments Formulation,” *AEÜ International Journal of Electronics and Communications*, vol. 54, no. 1, 2000.
54. A. Gromov and V. Korenivski, “Electromagnetic Analysis of Layered Magnetic/Conductor Structures,” *Journal of Physics D: Applied Physics*, vol. 33, no. 7, pp. 773-779, Apr. 2000.
55. T.W. Hertel and G.S. Smith, “The Insulated Linear Antenna–Revisited,” *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 6, pp. 914-920, June 2000.
56. V.I. Demidtchik, “Integral Equations for Dielectric-Coated Thin-Wire Antennas,” 8th *IEEE International Conference on Mathematical Methods in Electromagnetic Theory* (MMET), pp. 709-711, Kharkov, Ukraine, Sept. 12-15, 2000.
57. L.B. Cebik, W4RNL, “Note 50: The *NEC-4* IS Card – Insulated Wires,” *antenneX Online Magazine*, no. 60, Apr. 2002. Also in L.B. Cebik, W4RNL, *Antenna Modeling Notes, Volume 2*, pp. 391-405, antenneX Online Magazine, 2003, ISBN: 1877992550. Online at **http://on5au.be/content/amod/amod50.html**, **https://www.antenna2.net/cebik/content/amod/amod50.html**, or **https://www.antenna2.net/cebik/books/Antenna-Modeling-Notes-Vol-2.pdf**.
58. A.G. Boswell, G3NOQ, “Wire Coated with Dielectric – Equivalent Radius Calculation,” *antenneX Online Magazine*, no. 60, Apr. 2002.
59. I. Ida, J. Sato, T. Sekizawa, H. Yoshimura, and K. Ito, “Dependence of the Efficiency-Bandwidth Product on Electrical Volume of Small Dielectric Loaded Antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 6, pp. 821-826, June 2002.
60. M.U. Sitsko and V.I. Demidtchik, “Reflective Properties of Grid Structures with Dielectric Coating,” *9th International Conference on Mathematical Methods in Electromagnetic Theory* (MMET), pp. 420-422, Kiev, Ukraine, September 10-13, 2002.
61. X. Li, K. El Khamlichi Drissi, and F. Paladian, “Fast Efficient Method for Analysis of Insulated Wire Antennas Above Ground,” *Electronics Letters*, vol. 39, no. 13, pp. 951-953, June 25, 2003.
62. X. Li, K. El Khamlichi Drissi, and F. Paladian, “A Galerkin Moment Method for the Analysis of Insulated Wires Above a Lossy Half-Space,” *Annales des Telecommunications*, vol. 58, nos. 7-8, pp. 1157-1177, July/Aug. 2003.
63. J. Nadobny, R. Pontalti, D. Sullivan, W. Wlodarczyk, A. Vaccari, P. Deuflhard, and P. Wust, “A Thin-Rod Approximation for the Improved Modeling of Bare and Insulated Cylindrical Antennas Using the FDTD Method,” *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 1780-1796, Aug. 2003.
64. V.I. Demidchik and N.U. Sitsko, “Investigation of Integral Equation for Dielectric-Coated Thin-Wire Conductors,” *4th Int. Conf. on Antenna Theory and Techniques*, (ICATT), pp. 723-725, Sevastopol, Crimea, Ukraine, Sept. 9-12, 2003.
65. D. Fedorov, UA3AVR, “Calculation of the Model of an Antenna with Wires in Dielectric Insulation,” from *NEC-2* for *MMANA* “about” page, Sept. 27, 2003, **http://www.qsl.net/ua3avr/Read_me_Eng.htm**.
66. X. Li, K. El Khamlichi Drissi, and F. Paladian, “Insulated Vertical Antennas Above Ground,” *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 1, pp. 321-324, Jan. 2004.
67. C.A. Balanis, *Antenna Theory: Analysis and Design*, 3rd edition, Wiley, 2005. pp. 513-515.
68. V.I. Demidchik and N.U. Sitsko, “Range Properties of Cylindrical Helical Antennas Made of a Conductor with Dielectric Coating,” *5th International Conference on Antenna Theory and Techniques* (ICATT), pp. 295-297, Kyiv, Ukraine, May 24-27, 2005.
69. L.B. Cebik, W4RNL, “Note 83: Insulated Wires – The *NEC-2* Way,” *antenneX Online Magazine*, no. 97, May 2005. Also in L.B. Cebik, W4RNL, *Antenna Modeling Notes, Volume 4*, pp. 124-141, antenneX Online Magazine, 2006, ISBN: 187799278X. Online at **http://on5au.be/content/amod/amod83.html**, **https://www.antenna2.net/cebik/content/amod/amod83.html**, **https://www.antenna2.net/cebik/books/Antenna-Modeling-Notes-Vol-4.pdf**.
70. K.M.Z. Shams and M. Ali, “The Input Impedance of a Dipole Antenna Loaded by a Cylindrical Shell of Double Negative (DNG) Meta-Material,” abstract, *IEEE International Symposium on Antennas and Propagation*, Washington, DC, July 3-8, 2005.
71. K.M.Z. Shams and M. Ali, “Analyses of a Dipole Antenna Loaded by a Cylindrical Shell of Double Negative (DNG) Metamaterial,” *International Journal of Antennas and Propagation* (Hindawi), 2007.
72. D. Jaisson, “Simple Model for the Input Impedance of a Wire Monopole Radiator with a Dielectric Coat,” *IET Microwave Antennas Propagatation*, vol. 2, no. 4, pp. 316-323, June 2008.
73. Y. Kim, K.H. Koo, and S. Nam, “Method of Auxiliary Sources for the Analysis of Insulated Wire Antennas,” *IEEE International Symposium on Antennas and Propagation*, San Diego, CA, July 5-11, 2008.
74. S.D. Stearns, K6OIK, “Antenna Modeling for Radio Amateurs,” *ARRL Pacificon Antenna Seminar*, slides 40-41, San Ramon, CA, Oct. 17-19, 2008.
75. A. Adekola, A.I. Mowete, and A. Ogunsola, “On the Problem of Dielectric Coated Thin Wire Antenna,” *PIER Symp*. (PIERS), Moscow, Aug. 18-21 2009.
76. A.I. Mowete and A. Ogunsola, “Plane Wave Scattering by a Coated Thin Wire,” *PIER Symp*. (PIERS), pp. 743-749, Xi’an, China, Mar. 22-26, 2010.
77. A.I. Mowete and A. Ogunsola, “A Quasi-Static Theory for Dielectric-Coated Thin-Wire Antenna Structures,” *Progress in Electromagnetics Research Letters*, vol. 20, pp. 45-54, 2011.
78. C.A. Balanis, *Advanced Engineering Electromagnetics*, 2nd edition, Wiley, 2012. Chapter 2.
79. C-F. Wang, L.B. Kong, F-G. Hu, Z. Yang, and Z-W. Li, “Electrically Small Magneto-Dielectric Coated VHF Monopole Antenna,” *IEEE International Symposium Antennas and Propagation*, Chicago, IL, July 8-14, 2012.
80. C-F. Wang, L.B. Kong, F-G. Hu, Z. Yang, and Z-W. Li, “Electrically Small Magneto-Dielectric Coated Monopole Antenna at HF Band,” *IEEE Asia-Pacific Conference on Antennas and Propagation* (APCAP), Singapore, Aug. 27-29, 2012.
81. Y. Liao, T.H. Hubing, and D. Su, “Equivalent Circuit for Dipole Antennas in a Lossy Medium,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 8, pp. 3950-3953, Aug. 2012.
82. Y. Liao, T.H. Hubing, and D. Su, “Equivalent Circuit With Frequency-Independent Lumped Elements for Coated Wire Antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 11, pp. 5419-5423, Nov. 2012.
83. A. Zangwill, *Modern Electrodynamics*, Cambridge University Press, 2013. Chapters 6, 13, and 14.
84. T. Sebastian, *Magneto-Dielectric Wire Antennas: Theory and Design*, Ph.D. dissertation, Arizona State University, May 2013.
85. A.S. Yurkov, RA9MB/UA3AVR, “Simulation of Wire Antennas Coated by Dielectric by Means of NEC-2 Code,” (translated from Russian), *Tekhnika Radiosvyazi*, 2015.
86. S.D. Stearns, K6OIK, “Antenna Modeling for Radio Amateurs,” *ARRL Pacificon Antenna Seminar*, slides 51-53, San Ramon, CA, Oct. 14-16, 2016.
87. S.D. Stearns, K6OIK, “Antenna Modeling for Radio Amateurs – Revised and Expanded,” *ARRL Pacificon Antenna Seminar*, slides 58-62, San Ramon, CA, Oct. 20-22, 2017. Archived at **https://www.fars.k6ya.org/docs/k6oik**.

88. Y.G. Antonov, S.V. Ballandovich, G.A. Kostikov, L.M. Liubina, and M.I. Sugak, "Quality Factor and Radiation Efficiency of Electrically Small Antenna with Lossy Magnetodielectric Cover," *Conference of Russian Young Researchers in Electrical and Electronic Engineering* (ElConRus), Saint Petersburg, Russia, Jan. 25-28, 2022.
89. S.D. Stearns, K6OIK, "Grow an Antenna … from Seeds," *ARRL Pacificon Antenna Seminar*, slides 22-26, San Ramon, CA, Oct. 20-22, 2023. Archived at **https://www.fars.k6ya.org/docs/k6oik**.
90. S.D. Stearns, K6OIK, "Modeling Insulated Wire," Supplemental file for chapter 5 of *The ARRL Antenna Book*, 25th edition, American Radio Relay League, 2023. Archived at **http://www.arrl.org/files/file/Modeling%20Insulated%20Wire%20-%20K6OIK.pdf**.
91. D. Maguire, AC6LA, "*EZNEC* now does insulated wires with *NEC-5*," *QRZ.com*, April 15, 2024. Post at **https://forums.qrz.com/index.php?threads/eznec-now-does-insulated-wires-with-nec-5.910179**.

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March 6 – 9, 2025

Pasadena, California

www.socallinuxexpo.org/scale/22x

The 22nd Annual Southern California Linux Expo, SCaLE 22x, will take place March 6 – 9, 2025, at the Pasadena Convention Center in Pasadena, California.

Utah Digital Communications Conference

February 22, 2025

Sandy, Utah

https://utah-dcc.square.site

The Utah Digital Communications Conference will be held February 22, 2025, in Sandy, Utah.

2025 Central States VHF Conference

July 24 – 27, 2025

Lincoln, Nebraska

https://2025.csvhfs.org

The 2025 Central States VHF Conference will be held July 24 – 27, 2025, at the Lincoln North Hotel and Conference Center in Lincoln, Nebraska.

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