Small Loop and Analysis
Calculation For the Small HF Loop

Kai Siwiak, KE4PT **2017 Dec 28**

Note that the loop is in the XY plane in this analysis!

This Mathcad-based analysis is the basis of the small loop compliance distances published in FCC OET65 and "RF Exposure and You," ARRL, Newington CT, 1998. This analysis uses current and electric charges for small loops calculated from:

- J. E. Storer, "Impedance of thin wire loop antennas," NRL Rep. 212, Cambridge MA, May 1, 1955.
- K. Siwiak, "Loop Antennas," in John G. Proakis (Ed.), **Wiley Encyclopedia of Telecommunications**, New York, NY: John Wiley & Sons, 2002, pp 1290-1299.
- Q. Balzano, K. Siwiak. "Radiation of Annular Antennas," *Correlations,* Motorola Engineering Bulletin, Motorola Inc., Schaumburg, IL, USA, Volume VI, No. 2, Winter 1987.
- Q. Balzano, K. Siwiak. "The Near Field of Annular Antennas," *IEEE Transactions on Vehicular Technology*, Vol. VT-36, No. 4, pp. 173-183, November 1987.
- J. H. Dunlavy Jr., "Wide range tunable transmitting loop," U. S. Patent 3,588,905, 28 June, 1971.

Fields equations are from:

- Ronold W. P. King, Charles W. Harrison, Jr., Antennas and Waves: A Modern Approach, MIT Press, Cambridge, MA, 1969.

The loop is circular with radius b meters and wire radius a meters and is **oriented in the xy plane** with a feed gap on the x-axis (ϕ=0 deg). The wire cross section is measured by angle ψ with ψ=0 deg aligned with the x-axis. Detail of the current along the cross section of the wire is shown and can be included for results that are valid to within a wire radius of the antenna.

The power supplied to the loop can be adjusted by a factor of $F=1.6^2$ to account for a worst case ground refection, but the ground reflection is NOT otherwise explicitly calculated.

For specific cases: enter power P watts, loop wire radius a, loop radius b meters, frequency f MHz, and lopp conductivity σ mho/m.

In this specific case results are for a 0.90678 m diameter loop of 0.320 inch diameter aluminum wire at 7-30 MHz. The loop is constructed from RGC-213 coax; outer conductor is aluminum foil over copper braid. Inner copper conductor not included. This is close to the dimensions of the *AlexLoop* by Alex Geimberg, PY1AHD.

Loop Radiation Fields

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Loop is in the xy plane, current is non-constant, a<b<wavelength

FCC ground field factor: 1.6 $F := 1.6^2$ $F := 1$

dimensions in meters

Power supplied, W $Pw := 5$ $P := Pw \cdot F$ $P = 5$

Loop radius, m $b := 35.7 \cdot 0.5 \cdot 0.0254$ $b = 0.45339$

Wire radius, m $a := 0.320 \cdot 0.5 \cdot 0.0254$

Freq, MHz: $f := 14.1$ $a_{inner} := \frac{a}{2.84} \cdot 0$

Ground factor accounted for by increasing power to loop; all fields, currents, voltages then use P, not Pw, in free space.

conductivity, mho/m: $\sigma := 34 \cdot 10^6$ $\sigma_{in} := 58 \cdot 10^6$

Cu is $58x10^6$, Aluminum is 34 $x10^6$ mho/m
Tin is $8.7x10^6$; solders are ~ $8x10^6$
Alloy AIC12200 is 80%Cu= $46x10^6$

Added resistance: $Ra := 0.0$

The estimated loop matching circuit Qmatch (unloaded), not including loop resisitivity is:

Qmatch includes capacitor Q: $Qmatch := 2400$ (use 10^9 for no matching network losses)

$c := 299792456$ $\mu := 4 \cdot \pi \cdot 10^{-7}$ $\varepsilon := \frac{1}{\mu \cdot c^2}$ $\lambda := \frac{c}{f \cdot 10^6}$ $\Omega := 2 \cdot \ln\left(\frac{2 \cdot \pi \cdot b}{a}\right)$

$\omega := 2 \cdot \pi \cdot f \cdot 10^6$ $k := \omega \cdot \sqrt{\mu \cdot \varepsilon}$

$\eta := c \cdot \mu$ $\delta := \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}}$ $Zloss := \left[\frac{2 \cdot \pi \cdot (a \cdot \delta \cdot \sigma)}{2 \cdot \pi \cdot b} + \frac{2 \cdot \pi \cdot (a_{inner} \cdot \delta \cdot \sigma_{in})}{2 \cdot \pi \cdot b}\right]^{-1} \cdot (1 + j)$ inner and outer coax conductors in parallel

Computed constants: $Rloss := Re(Zloss)$ loop conductor resistance

$\frac{a}{\delta} = 176.8$ $k = 0.296$ $Rloss = 0.143$ $a \cdot 1000 = 4.064$ mm

$k \cdot b = 0.134$ $\Omega = 13.105$ $b = 0.45339$ m

(Z, **including higher order terms** for, (kb) < 0.4:)

M12 HF model from LOOP-M12-coupling-to-smaller-loop-ZX-plane.mcd

$M12 := 5.73045 \cdot 10^{-8} - j \cdot 2.06145 \cdot 10^{-11}$

$$Z(k,b,a) := \eta \cdot \frac{\pi}{6} \cdot (k \cdot b)^4 \cdot \left[1 + 8 \cdot (k \cdot b)^2\right] \cdot \left[1 - \left(\frac{a}{b}\right)^2\right] + j \cdot \omega \cdot \left[\mu \cdot b \cdot \left[\ln\left(8 \cdot \frac{b}{a}\right) - 2 + \frac{2}{3} \cdot (k \cdot b)^2\right] + M12\right] \cdot \left[1 + 2 \cdot (k \cdot b)^2\right]$$

This impedance is for ONLY the loop, low freq inductance: $Z1(k,b,a) := \eta \cdot \frac{\pi}{6} \cdot (k \cdot b)^4 + j \cdot \eta \cdot k \cdot b \cdot \left(\ln\left(8 \cdot \frac{b}{a}\right) - 2\right)$ $Z1(k,b,a) = 0.064 + 241.981i$

$Qrad := 0.5 \cdot \frac{Im(Z(k,b,a))}{Re(Z(k,b,a))}$ loaded radiation Q $Qrad = 1.72 \times 10^3$

loop impedance (no loss): $Z(k,b,a) = 0.07458 + 256.55361i$ $\eta \cdot \frac{\pi}{6} \cdot (k \cdot b)^4 = 0.06357$

loop impedance including wire skin depth and added loss: $Zloop := Z(k,b,a) + Zloss + Ra$

$Zloop = 0.21733 + 256.69636i$ $\frac{Im(Zloop)}{\omega} = 2.897 \times 10^{-6}$

The total loaded (transmitter connected) QL includes Qrad, loop resistive loss Q, and the Qmatch:

$$QL := \frac{0.5}{\frac{1}{Qmatch} + \frac{Re(Zloop)}{Im(Zloop)}}$$

$QL = 395.78706$ $\quad Rr := Re(Z(k,b,a))$

$Qmatch = 2.4 \times 10^{3}$ $\quad Rr = 0.075$ radiation resistance

$Qrad = 1.72 \times 10^{3}$ $\quad Rloss = 0.143$ conductivity loss

$$Io := \sqrt{\frac{P}{Rr} \cdot \frac{QL}{Qrad}}$$

$Io = 3.928$ A, rms

$$eff := \frac{Io^{2} \cdot Rr}{P}$$

$eff \cdot 100 = 23.012$ % $\quad \frac{QL}{Qrad} \cdot 100 = 23.012$ %

$10 \cdot \log(eff) = -6.381$

$$Cresonance := \frac{1}{\omega \cdot Im(Zloop)}$$

$\frac{f \cdot 1000}{QL} = 35.625$ kHz BW $\quad Cresonance \cdot 10^{12} = 43.973$ pF

$$Vcap := \sqrt{2 \cdot |Im(Zloop)| \cdot QL \cdot Pw}$$

$\frac{Vcap}{\sqrt{1}} = 1007.954$ Peak volts

Current Density, wire; radius a, loop radius b:
ϕ = loop circumference, 0 = feed gap
ψ = wire circumference, 0 = outside of loop
Loop is in x-y plane

$$Y(a,b) := -\left(\frac{2 \cdot a}{10 \cdot a + b}\right)^{0.75}$$

$$J(\phi,\psi) := \frac{Io}{2 \cdot \pi \cdot a} \cdot \left[1 - 2 \cdot \cos(\phi) \cdot (k \cdot b)^{2}\right] \cdot (1 + Y(a,b) \cdot \cos(\psi))$$

The loop current variation around the wire with a feed gap on the +x axis is:

$$I(\phi) := Io \cdot \left[1 - 2 \cdot \cos(\phi) \cdot (k \cdot b)^{2}\right] \qquad J(\phi) := \frac{Io}{2 \cdot \pi \cdot a} \cdot \left[1 - 2 \cdot \cos(\phi) \cdot (k \cdot b)^{2}\right]$$

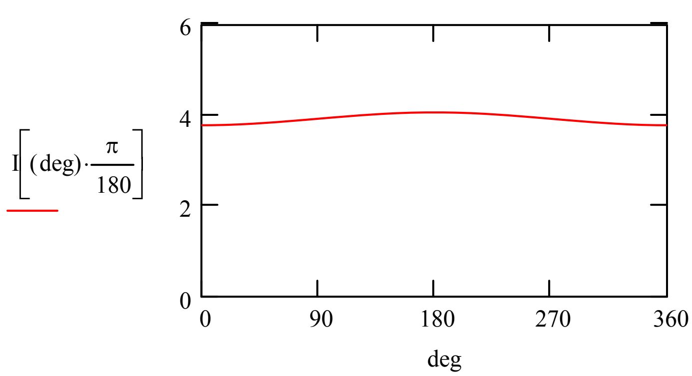
$$q(\phi) := \frac{1}{-j \cdot \omega \cdot \rho} \cdot \frac{d}{d\phi} I(\phi) \qquad q(\phi) := \frac{Io \cdot (k \cdot b)^{2}}{-j \cdot \omega \cdot b} \cdot 2 \cdot \sin(\phi) \qquad E_s(\phi) := \frac{q(\phi)}{\varepsilon \cdot 2 \cdot \pi \cdot a} \qquad H_s(\phi) := J(\phi)$$

$$C_\lambda := k \cdot b \qquad I(\phi) := Io \cdot \left[1 - 2 \cdot \cos(\phi) \cdot (C_\lambda)^{2}\right]$$

$E_s\left(\frac{\pi}{2}\right) = 1.553i \times 10^{4}$ $\quad H_s\left(\frac{\pi}{2}\right) = 153.818$

$deg := 0 .. 360$ Loop current around loop circumference

$I(0) = 3.787$



$2 \cdot (k \cdot b)^{2} = 0.036$ $\quad$ loop area, λ^2

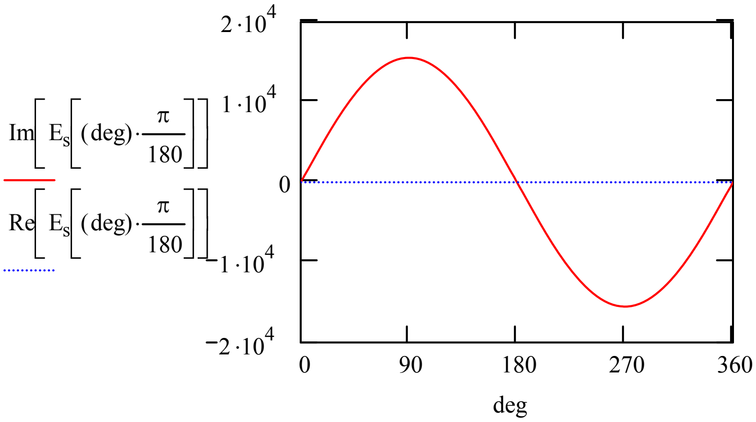
$k \cdot b = 0.134$ $\quad I(0) = 3.787$

$b = 0.453$ $\quad I(\pi) = 4.069$

$f = 14.1$ $\quad Io = 3.928$

$2 \cdot C_\lambda^{2} = 0.036$

$deg := 0..360$ Surface Electric field around loop circumference, normal to the loop wire:



loop area, λ^2:

$2\cdot(k\cdot b)^2 = 0.036$

$k\cdot b = 0.134$

$b = 0.453$

$f = 14.1$

$u := 0.78$

Peak surface electric field is at:

$PHI := root\left(\frac{d}{du}Im\left(E_S(u)\right), u\right)$ $PHI\cdot\frac{180}{\pi} = 90$ deg. $Esp := E_S(PHI)$ $Esp = 15528.122i$

Vector potential for the loop in the xy plane:

$$C := \frac{b\cdot\mu}{4\cdot\pi}$$

$$Ax(x,y,z) := C\cdot\int_0^{2\cdot\pi} I(\phi)\cdot\frac{e^{-j\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}\cdot(-\sin(\phi))\,d\phi$$

$$Ay(x,y,z) := C\cdot\int_0^{2\cdot\pi} I(\phi)\cdot\frac{e^{-j\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}\cdot\cos(\phi)\,d\phi$$

Evaluate the y component of $\nabla\,\nabla\bullet A$

$$yA(x,y,z,\phi) := -\sin(\phi)\cdot\left[\frac{3}{4}\cdot i\cdot\frac{k\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^2}\ \ldots \\ +\frac{-1}{4}\cdot\frac{k^2\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\ \ldots \\ +\frac{3}{4}\cdot\frac{(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{5}{2}\right)}}\right]\ \ldots \\ +\cos(\phi)\cdot\left[\frac{3}{4}\cdot i\cdot\frac{k\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^2}\ \ldots \\ +-i\cdot\frac{k}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]}\ \ldots \\ +\frac{-1}{4}\cdot\frac{k^2\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\ \ldots \\ +\frac{3}{4}\cdot\frac{(2\cdot y-2\cdot b\cdot\sin(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{5}{2}\right)}}\ \ldots \\ +\frac{-1}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\right]$$

$$Ey(x,y,z) := -j\cdot\omega\cdot Ay(x,y,z)+\frac{C}{j\cdot\omega\cdot\mu\cdot\varepsilon}\cdot\int_0^{2\cdot\pi} I(\phi)\cdot yA(x,y,z,\phi)\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}\,d\phi$$

Evaluate the x component of $\nabla \nabla \bullet A$

$$xA(x,y,z,\phi) := -\sin(\phi)\cdot\left[\frac{3}{4}\cdot i\cdot\frac{k\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^2}\ldots \atop + i\cdot\frac{-k}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]}\ldots\right]\ldots$$

$$\left[\ldots + \frac{-\frac{1}{4}\cdot k^2\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\ldots + \frac{3}{4}\cdot\frac{(2\cdot x-2\cdot b\cdot\cos(\phi))^2}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{5}{2}\right)}}\ldots + \frac{-1}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\right]$$

$$+\cos(\phi)\cdot\left[\frac{3}{4}\cdot i\cdot\frac{k\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^2}\ldots + \frac{-\frac{1}{4}\cdot k^2\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\ldots + \frac{3}{4}\cdot\frac{(2\cdot x-2\cdot b\cdot\cos(\phi))\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{5}{2}\right)}}\right]$$

$$Ex(x,y,z) := -j\cdot\omega\cdot Ax(x,y,z)+\frac{C}{j\cdot\omega\cdot\mu\cdot\varepsilon}\cdot\int_0^{2\cdot\pi} I(\phi)\cdot xA(x,y,z,\phi)\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}\,d\phi$$

$$Hy(x,y,z) := \frac{C}{\mu}\cdot\left[\int_0^{2\cdot\pi} I(\phi)\cdot(-\sin(\phi))\cdot\left[\frac{-j\cdot k\cdot z\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}\ \ldots\ + \frac{-e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\cdot z\right]d\phi\right]$$

$$Hx(x,y,z) := \frac{C}{\mu}\cdot\left[\int_0^{2\cdot\pi} I(\phi)\cdot(\cos(\phi))\cdot\left[\frac{-j\cdot k\cdot z\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}\ \ldots\ + \frac{-e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\cdot z\right]d\phi\right]$$

$$Hz(x,y,z) := \frac{C}{\mu}\cdot\left[\int_0^{2\cdot\pi} I(\phi)\cdot\frac{\sin(\phi)}{2}\cdot\left[\frac{-i\cdot k\cdot(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}\ \ldots\ + \frac{-(2\cdot y-2\cdot b\cdot\sin(\phi))\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\right]d\phi\ \ldots\ + \int_0^{2\cdot\pi} I(\phi)\cdot\frac{\cos(\phi)}{2}\cdot\left[\frac{-i\cdot k\cdot(2\cdot x-2\cdot b\cdot\cos(\phi))\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}\ \ldots\ + \frac{-(2\cdot x-2\cdot b\cdot\cos(\phi))\cdot e^{-i\cdot k\cdot\sqrt{(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2}}}{\left[(x-b\cdot\cos(\phi))^2+(y-b\cdot\sin(\phi))^2+z^2\right]^{\left(\frac{3}{2}\right)}}\right]d\phi\right]$$

$$ET(x,y,z) := \sqrt{(|Ex(x,y,z)|)^2 + (|Ey(x,y,z)|)^2} \qquad E_s(\phi) := \frac{q(\phi)}{\varepsilon \cdot 2 \cdot \pi \cdot a}$$

$$HT(x,y,z) := \sqrt{(|Hx(x,y,z)|)^2 + (|Hy(x,y,z)|)^2 + (|Hz(x,y,z)|)^2} \qquad H_s(\phi) := J(\phi) \qquad u := 10$$

Check if the field point is within u% of inside of the loop toroidal surface, replace with the value at the surface for later computational convenience:

$$inToroid(x,y,z) := if\left[\sqrt{\left(\sqrt{x^2+y^2} - b\right)^2 + z^2} \le a \cdot \left(1 + \frac{u}{100}\right), 1, 0\right]$$

$$Et(x,y,z) := if\left[inToroid(x,y,z), |E_S(arg(x + j \cdot y))|, \sqrt{(|Ex(x,y,z)|)^2 + (|Ey(x,y,z)|)^2}\right]$$

$$Ht(x,y,z) := if\left[inToroid(x,y,z), |H_S(arg(x + j \cdot y))|, \sqrt{(|Hx(x,y,z)|)^2 + (|Hy(x,y,z)|)^2 + (|Hz(x,y,z)|)^2}\right]$$

<u>Sanity Checks...</u> at large distance, dd: $dd := \frac{1000}{k}$ $\quad k = 0.296 \quad f = 14.1$

For <u>vanishingly</u> small loop: $Ephi(r) := \eta \cdot \frac{k^3 \cdot Io \cdot \pi \cdot b^2}{4 \cdot \pi} \cdot \left[\frac{1}{k \cdot r} - \frac{j}{(k \cdot r)^2}\right]$ $\quad \frac{|Ephi(dd)|}{Et(0,dd,0)} = 1.002$

Solenoid: $H000 := \frac{Io}{2 \cdot b}$ $\quad H000 = 4.33151 \quad E000 := -j \cdot \eta \cdot \frac{k}{2} \cdot Io \quad E000 = -218.63545i$

Exact: $Hz(0,0,0) = 4.370219 - 3.466485i \times 10^{-3}$ $\quad Ey(0,0,0) = 0.349 - 216.699i$

$Ex(0,0,0) = 1.04323 \times 10^{-13} + 8.86085i \times 10^{-13}$

Wave impedance at center of loop: $\frac{Et(0,0,0)}{Ht(0,0,0)} = 49.58553$ $\quad Z000 := -j \cdot k \cdot b \cdot \eta \quad |Z000| = 50.4755177$

$Z(k,b,a) + Zloss = 0.217329 + 256.69636i$

resonating cap voltage:

$QL := 0.5 \cdot \frac{Im(Z(k,b,a))}{Re(Z(k,b,a)) + Rloss}$ $\quad QL = 590.242$

$Vcap := \sqrt{2 \cdot Im(Z(k,b,a)) \cdot QL \cdot Pw}$

$Vcap = 1230.5639$ V peak, for Pw not P!

Far field distance, m: $dd := \lambda \cdot 10^9$ $\quad P = 5 \quad Pw = 5$

Far Field check: ratio approaches 1 for extremely small loop:

$$\frac{Ht(dd,dd,0)}{\frac{\sqrt{\frac{P \cdot eff \cdot 1.5}{4 \cdot \pi \cdot \eta}}}{dd \cdot \sqrt{2}}} = 0.93738 \qquad \frac{Et(dd,dd,0)}{\frac{\sqrt{\frac{P \cdot eff \cdot 1.5 \cdot \eta}{4 \cdot \pi}}}{dd \cdot \sqrt{2}}} = 0.93738$$

Approximate far field null depth: $nullFAR := 20 \cdot \log[2(k \cdot b)]$ $\quad nullFAR = -11.438$

$null4nec2\_14 := -11.5$ dB at 14.1 MHz

"Null depth" in the far field (loop is in xy-plane), on axis, relative to peak in x, peak in z:

$dd = 2.126 \times 10^{10}$ m $(k \cdot b) = 0.134$ $f = 14.1$

$\frac{Ht(0,0,dd)}{Ht(dd,0,0)} = 0.259495$ $Null := 20 \cdot \log\left(\frac{Ht(0,0,dd)}{Ht(dd,0,0)}\right)$ $Null = -11.717$ dB

$\frac{Ht(0,0,dd)}{Ht(0,dd,0)} = 0.268568$ $Null := 20 \cdot \log\left(\frac{Ht(0,0,dd)}{Ht(0,dd,0)}\right)$ $Null = -11.419$ dB

$nullFAR = -11.438$

$\frac{Et(0,0,dd)}{Et(0,dd,0)} = 0.268568$ $Null := 20 \cdot \log\left(\frac{Et(0,0,dd)}{Et(0,dd,0)}\right)$ $Null = -11.419$ dB

$\frac{Et(0,0,dd)}{Et(dd,0,0)} = 0.259495$ $Null := 20 \cdot \log\left(\frac{Et(0,0,dd)}{Et(dd,0,0)}\right)$ $Null = -11.717$ dB

Perturb the far field location by dx around x and y, seek for off axis null:

$NullX(dx) := 20 \cdot \log\left(\frac{Ht(dx,0,dd)}{Ht(0,dd,0)}\right)$ $NullX(0) = -11.419$ dB

$NullY(dx) := 20 \cdot \log\left(\frac{Ht(0,dx,dd)}{Ht(0,dd,0)}\right)$ $NullY(0) = -11.419$ dB

Off the main axes:

$NullOffp(dx) := 20 \cdot \log\left(\frac{Ht\left(\frac{dx}{\sqrt{2}}, \frac{dx}{\sqrt{2}}, dd\right)}{Ht(0,dd,0)}\right)$ $NullOffp(0) = -11.419$ dB

$NullOffm(dx) := 20 \cdot \log\left(\frac{Ht\left(\frac{-dx}{\sqrt{2}}, \frac{dx}{\sqrt{2}}, dd\right)}{Ht(0,dd,0)}\right)$ $NullOffm(0) = -11.419$ dB

$dxi := 0 .. 10$ $scale := 100$ $DX_{dxi} := (-5 + dxi) \cdot scale$

$f = 14.1$

$DX_{dxi} =$	$NullX(DX_{dxi}) =$	$NullY(DX_{dxi}) =$	$NullOffp(DX_{dxi}) =$	$NullOffm(DX_{dxi}) =$
-500	-11.419	-11.419	-11.419	-11.419
-400	-11.419	-11.419	-11.419	-11.419
-300	-11.419	-11.419	-11.419	-11.419
-200	-11.419	-11.419	-11.419	-11.419
-100	-11.419	-11.419	-11.419	-11.419
0	-11.419	-11.419	-11.419	-11.419
100	-11.419	-11.419	-11.419	-11.419
200	-11.419	-11.419	-11.419	-11.419
300	-11.419	-11.419	-11.419	-11.419
400	-11.419	-11.419	-11.419	-11.419
500	-11.419	-11.419	-11.419	-11.419

Search result: the null is symetrical, and on the x=0, y=0, z-axis

Omitting the ϕ current term would results in an extremely deep null!

Near Fields: $dx_{dxi} := -0.7 + dxi \cdot 0.14$ $b = 0.453$

The loop gap is in the +x-axis **There is symmetry about y-axis**

$dx_{dxi} =$	$Et(dx_{dxi},0,0) =$	$Ht(dx_{dxi},0,0) =$	$\frac{Et(dx_{dxi},0,0)}{Ht(dx_{dxi},0,0)} =$	$Et(0,dx_{dxi},0) =$	$Ht(0,dx_{dxi},0) =$	$\frac{Et(0,dx_{dxi},0)}{Ht(0,dx_{dxi},0)} =$
-0.7	13.434	1.125	11.94	191.937	1.065	180.251
-0.56	59.715	3.865	15.45	556.084	3.7	150.3
-0.42	214.779	22.871	9.391	$1.825 \cdot 10^3$	22.136	82.461
-0.28	176.182	6.451	27.312	380.002	6.312	60.207
-0.14	189.411	4.761	39.781	245.267	4.71	52.079
0	216.7	4.37	49.586	216.7	4.37	49.586
0.14	260.087	4.658	55.84	245.267	4.71	52.079
0.28	338.108	6.172	54.777	380.002	6.312	60.207
0.42	600.229	21.401	28.047	$1.825 \cdot 10^3$	22.136	82.461
0.56	269.408	3.535	76.222	556.084	3.7	150.3
0.7	126.935	1.005	126.364	191.937	1.065	180.251

Loop center: i=5

$dx_5 = 0$ $Et(dx_5,0,0) = 216.7$ $Et(0,dx_5,0) = 216.7$

$Ht(dx_5,0,0) = 4.37$ $Ht(0,dx_5,0) = 4.37$

$Z000 := -j \cdot k \cdot b \cdot \eta$ $|Z000| = 50.4755177$ $\frac{Et(dx_5,0,0)}{Ht(dx_5,0,0)} = 49.586$ $\frac{Et(0,dx_5,0)}{Ht(0,dx_5,0)} = 49.586$