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Loop Proximity Effects in Three-Loop Antenna Systems

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Abstract

Three-loop antenna systems (TLASs) are one of the few sensors with the ability to simultaneously detect all of the components of the electromagnetic field. The theory of TLASs ignores the presence of the other orthogonal loops and assumes that the response is that of a dual-loaded loop in isolation. This paper investigates the loop proximity effects for the cases of plane wave and centrally located dipole moment sources, as a function loop wire radius. It is shown through simulations that the responses of the TLAS sensor are unaffected by the presence of the other loops when considering just the magnetic field component of the plane wave and the magnetic dipole source. However, the TLAS reponses to the electric field component of the plane wave and the electric dipole moment can be significantly affected.

1 Introduction

A dual-loaded loop is a well known electromagnetic sensor capable of simultaneously detecting a component from each of the electric and magnetic incident field vectors [1]. Kanda extended the analysis of dual-loaded loops to cases of a general incident field [2]. Three-Loop Antenna Systems (TLASs) are composed of three orthogonal, dual-loaded loop antennas, capable of simultaneously measuring all six electromagnetic field components (i.e. three electric and three magnetic.) In a rich multipath environment these components are independent. Originally, the TLAS was proposed for magnetic field measurements for Electromagnetic Compatibility (EMC) measurements [3]. Kanda and Hill showed that TLASs are also capable of detecting the total electric and magnetic dipole moment vectors located at the centre of the loops [4]. The scattering and mutual coupling between the orthogonal dual-loaded loops in a TLAS was ignored, and the loop responses were assumed to match those of isolated loops in freespace.

This paper summarizes the response of the dual-loaded loop sensor to plane waves, and to electric and magnetic dipole moment sources. Using simulations, the response of an isolated dual-loaded loop sensor is compared to when the loop is used within a TLAS, i.e. in the presence of the other two orthogonal loops.

2 Theory

This section summarizes the theory of the response of dual-loaded loops to plane wave and dipole moment sources. Throughout this paper complex notation is used and the time harmonic factor, $e^{j\omega t}$, has been suppressed. The positive current direction is ϕ-direction.

2.1 Dual-loaded Loop Sensor Response to a General Electric Field

The sum and difference currents through the loads of an electrically small loop can be approximated in terms of the Fourier series coefficients of the tangential electric field on the loop [5],

$$I_\Sigma = I(\phi = 0) + I(\pi) = 2I_0 \approx -\frac{4\pi R Y_0}{1 + 2Z_L Y_0} f_0, \tag{1}$$

$$I_\Delta = I(0) - I(\pi) = 2\left(I_1 + I_{-1}\right) \approx -\frac{2\pi R Y_1}{1 + 2Z_L Y_1}\left(f_1 + f_{-1}\right), \tag{2}$$

where R is the loop radius, Z_L is the load impedance of the ports, Y_n is the loop port admittance of the n^{th} current mode, and f_n is the Fourier series n^{th} coefficient of the Fourier series expansion of the tangential electric fields along the wire loop.

2.1.1 Response to a Linearly Polarized Plane Wave

For a linearly polarized plane wave incident on a z-directed loop (i.e. centered on the origin within the xy-plane) with loads on the x-axis, the sum and difference currents are related to components of the electric and magnetic intensities [5],

$$I_\Sigma = I(0) + I(\pi) = \frac{j2\pi k R^2 \eta Y_0}{1 + 2Y_0 Z_L} H_z, \tag{3}$$

$$I_\Delta = I(0) - I(\pi) = -\frac{2\pi R Y_1}{1 + 2Y_1 Z_L} E_y. \tag{4}$$

where k is the wavenumber.

2.1.2 Response to electric and magnetic dipole moments at the origin

Electric and magnetic dipole moments located at the origin, can be expressed, respectively, as

$$\boldsymbol{m}_e = I\boldsymbol{\ell} = m_{e,x}\hat{\boldsymbol{x}} + m_{e,y}\hat{\boldsymbol{y}} + m_{e,z}\hat{\boldsymbol{z}}, \tag{5}$$

$$\boldsymbol{m}_m = I\boldsymbol{a} = m_{m,x}\hat{\boldsymbol{x}} + m_{m,y}\hat{\boldsymbol{y}} + m_{m,z}\hat{\boldsymbol{z}}, \tag{6}$$

where m_{ej} and m_{mj} are the components of the electric and magnetic dipole moment along the j^{th} coordinate, respectively, I is the current amplitude, $\boldsymbol{\ell}$ is the electric dipole's incremental length vector, and $\boldsymbol{a}$ is the magnetic dipole's incremental area vector in the direction normal to the loop (following the "right-hand rule" convention.)

For a z-directed loop (i.e. centered on the origin within the xy-plane) with loads along the x-axis, the sum and difference currents are related to the components of the moments [5], as

$$I_\Sigma = I(0) + I(\pi) = -\frac{4\pi R Y_0 G_m}{1 + 2Y_0 Z_L} m_{m,z}, \tag{7}$$

$$I_\Delta = I(0) - I(\pi) = -\frac{2\pi R Y_1 G_e}{1 + 2Y_1 Z_L} m_{e,y}, \tag{8}$$

where

$$G_m = \frac{\eta}{4\pi}\left(\frac{k^2}{R} - \frac{jk}{R^2}\right)e^{-jkR}, \tag{9}$$

$$G_e = -\frac{\eta}{4\pi}\left(\frac{jk}{R} + \frac{1}{R^2} + \frac{1}{jkR^3}\right)e^{-jkR}. \tag{10}$$

3 Experimental Results

TLAS loop proximity effects were investigated using CST Microwave Studio [6] time-domain simulations. Dual-loaded loops were first simulated in isolation and then compared against the loop's response in a TLAS, i.e. when in the presence of the other two orthogonal loops. The z-directed loop, i.e. the loop within the xy-plane, was used for all the comparisons. Three different loop wire radii were considered: $r_w = R/100$, $R/25$, and $R/14.3$, where r_w is the loop wire radius and the loop radius $R = 0.5$m. The port impedances were all $Z_L = 315\Omega$, so that there was a slightly different current response between the electric and magnetic field from the plane wave. The port gaps were fixed at $h = R/50$. The simulation model can be seen in Fig. 1. An important consideration for these investigations is how the orthogonal loops are offset from each other, as the orthogonal loops need to be offset so they do not touch galvanically. For this study, the loops were offset such that their separation distance from the other loops were a loop wire radius r_w.

3.1 Plane Wave Source

The port currents on a dual-loaded loop were obtained for a plane wave source, with and without the presence of

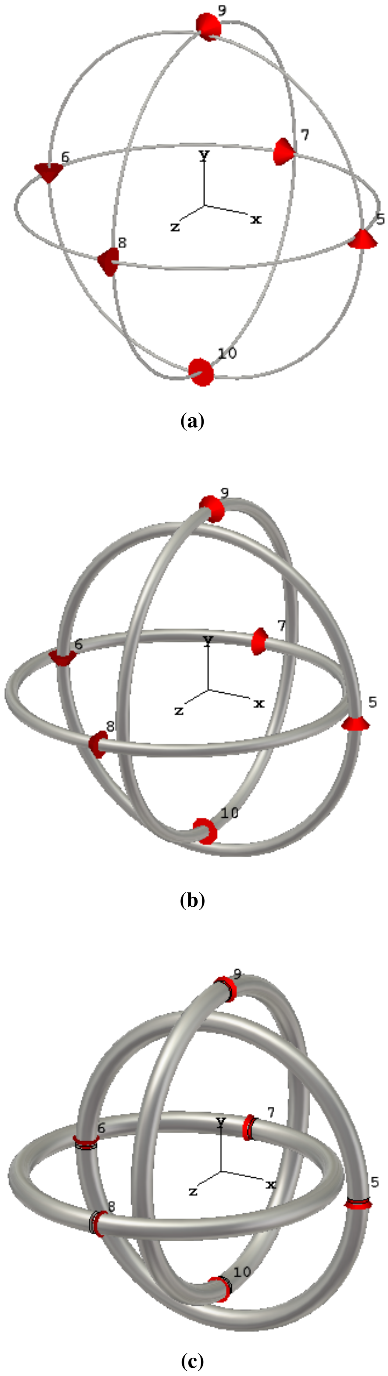


Figure 1. Simulation model to compare the response of a dual-loaded loops in isolation against in a TLAS. The loop radii were $R = 0.5$m and three different loop wire radii were considered: (a) $r_w = R/100$, (b) $R/25$ and (c) $R/14.3$. For each case, the loops were offset so that they were separated by a loop wire radius r_w.

the other orthogonal loops. The plane wave had a maximum electric intensity of 1V/m and propagating in the $+\hat{\boldsymbol{x}}$-direction with polarization in the $+\hat{\boldsymbol{y}}$-direction. Figure 2a shows the I_Σ responses, with Fig. 2b showing that the presence of the orthogonal loops have a minimal impact to the response to the magnetic field. Figure 2c shows the I_Δ responses, with Fig. 2d showing that the presence of the orthogonal loops affect the response to an electric field on the order of 2dB. The results are shown only up to $kR = 1$ since the loop is assumed to be electrically small. These results are not surprising given that the orientation of the orthogonal loops are such there is no magnetic flux passes through the two other orthogonal loops, however there is strong induced currents on one of the orthogonal loops (i.e. the x-orientated loop) from the electric field. This unavoidable induced current will perturb the electric field response, compared to the isolated loop, when sensing an electric plane wave.

3.2 Dipole Moment Sources

The dual-loaded loop port currents were simulated using centrally located electrically small dipole sources, with and without the presence of the other orthogonal loops. The electrically small dipole moment sources were modelled using CST's discrete current source ports.

3.2.1 Magnetic Dipole Moment

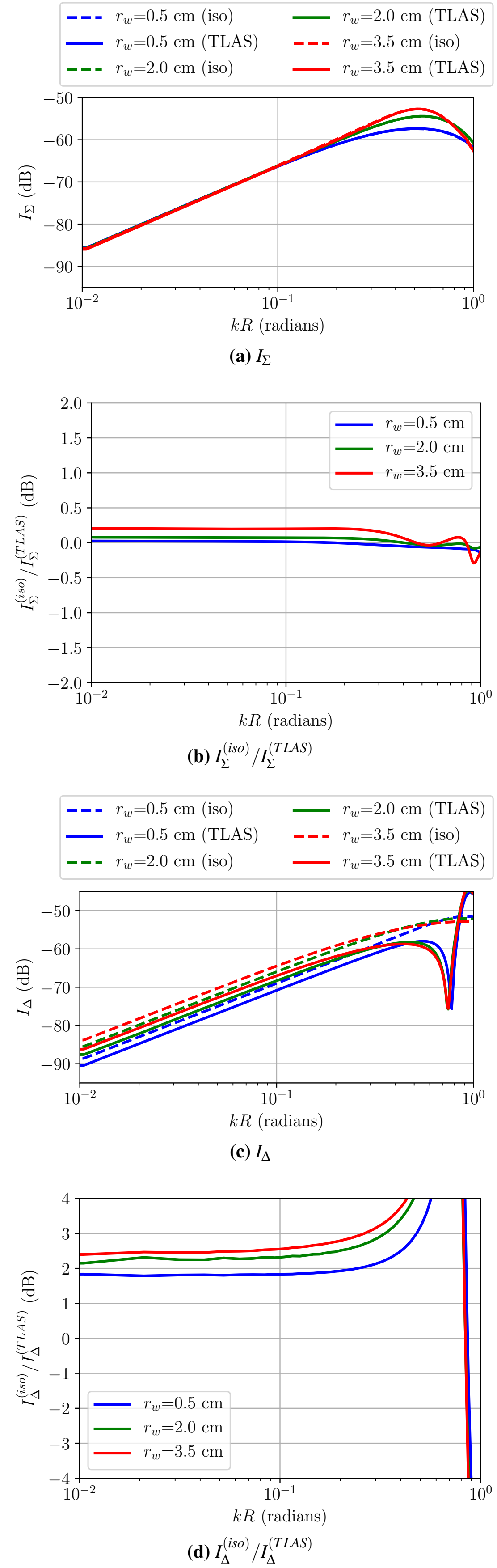
The electrically small magnetic dipole moment source was modelled as a square loop with 1.2mm edge lengths, 0.1mm thickness, with 1A current, located at the center of the z-directed loop. Figure 3a shows the response of dual-loaded loop with versus without the presence of the two orthogonal loops. Figure 3b shows that the presence of the other loops in a TLAS has very little impact (< 0.5dB) compared the response when the dual-loaded loop was in isolation when detecting magnetic dipole moments.

3.2.2 Electric Dipole Moment

The electrically small electric dipole moment was modelled as a 1mm long constant 1A current source, located at the center of the z-directed loop. Figure 4a shows the response of dual-loaded loop with versus without the presence of the two orthogonal loops. Figure 4b shows that the presence of the other loops in a TLAS cause a 2dB degradation when the wire is thin, i.e. $R/100$, to 4dB when the wire is thick, i.e. $R/14.3$.

4 Conclusion

The theory of Three-loop Antenna System ignores the scattering and mutual coupling between the orthogonal loops and assumes that the performance of each loops is that of a loop in isolation. This paper investigated this assumption through numerical experiments, as a function of loop wire thickness. For a plane wave source, the magnetic field



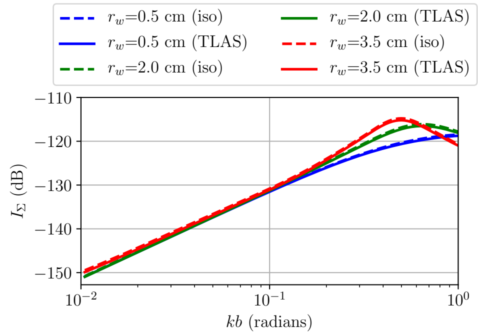
(a) I_Σ

(b) $I_\Sigma^{(iso)}/I_\Sigma^{(TLAS)}$

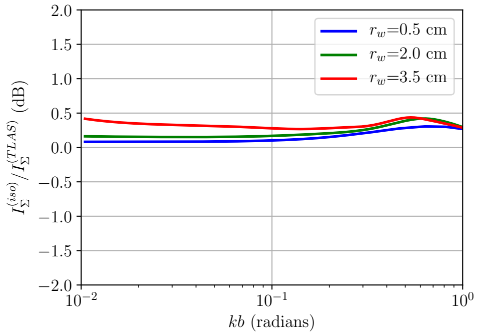
(c) I_Δ

(d) $I_\Delta^{(iso)}/I_\Delta^{(TLAS)}$

Figure 2. Current responses to a plane wave, when the loop was in isolation, $I^{(iso)}$, versus in a TLAS, $I^{(TLAS)}$.

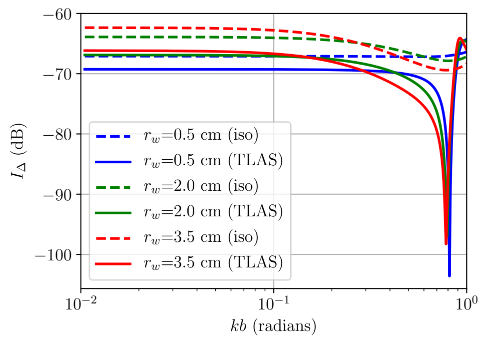


(a) I_Σ

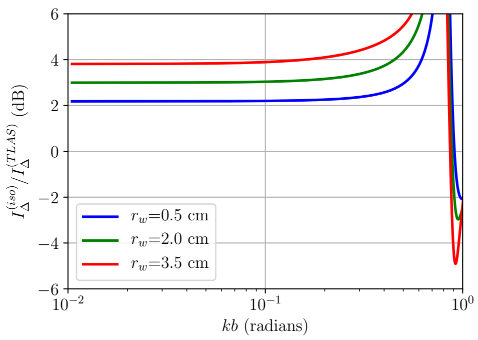


(b) $I_\Sigma^{(iso)}/I_\Sigma^{(TLAS)}$

Figure 3. Current response to a magnetic dipole source, when the loop was in isolation, $I^{(iso)}$, versus in a TLAS, $I^{(TLAS)}$.



(a) I_Δ



(b) $I_\Delta^{(iso)}/I_\Delta^{(TLAS)}$

Figure 4. Current response to an electric dipole source, when the loop was in isolation, $I^{(iso)}$, versus in a TLAS, $I^{(TLAS)}$.

response is unaffected by the presence of the other orthogonal loops, however the electric field response is shown to degrade by roughly 2.5dB. Similarly, the response to centrally located magnetic dipole moments is unaffected by the other loops, however for electric dipole moments there is a degradation of 2 to 4 dB depending on the thickness of the loops.

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