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Ground Plane 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 centrally located electric and magnetic dipole moment vectors. The theory of TLASs ignores the presence of ground planes and assumes that the responses comprise those of single dual-loaded loops in isolation. This paper investigates the ground plane proximity effects for the cases of centrally located electric or magnetic dipole moment sources, as a function ground plane separation distance. It is shown through simulations that the responses of the TLAS sensor are not significantly affected by the presence of a ground plane which is parallel to one of the loops. The only appreciable impact is that the margin of the source type discrimination decreases as the ground plane approaches the TLAS.

1 Introduction

Three-Loop antenna systems were first proposed as a sensor capable of simultaneously detecting all six electromagnetic field components, i.e. three electric and three magnetic [2]. In a rich multipath environment these components are independent. Shortly after its introduction, TLASs were shown to be able to detect centrally located electric or magnetic dipole moment vectors [3]. The theory of operation of a TLAS assumes that the responses of a dual-loaded loop sensors [1] are the same as a single loop in isolation. The scattering and mutual coupling between the orthogonal dual-loaded loops in a TLAS is ignored [4], as well as the potential effects of nearby ground planes. The performance change of van Veen loops (i.e. a magnet moment sensor) due to an semi-anechoic chamber has been investigated [5]. However, since the proximity of ground planes are unavoidable in practical deployments of TLASs, further investigation into their potential effects on the performance of TLASs is warranted.

This paper presents simulation results investigating how the presence of a nearby ground plane affects the response of a TLAS with centrally located electric or magnetic dipole moment sources. An infinite ground plane is located perpendicular to one of the Cartesian axis and the separation distance between a TLAS and a ground plane is varied. The experiment was repeated for the cases of when the ground plane was perpendicular to the other Cartesian axes. For this arrangement, it is shown that the ground plane has little effect on the performance.

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 [6],

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

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

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 electric and magnetic dipole moments at the origin

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

$$\boldsymbol{m}_e = I\boldsymbol{\ell} = m_{e,x}\hat{\boldsymbol{x}} + m_{e,y}\hat{\boldsymbol{y}} + m_{e,z}\hat{\boldsymbol{z}}, \tag{3}$$

$$\boldsymbol{m}_m = I\boldsymbol{a} = m_{m,x}\hat{\boldsymbol{x}} + m_{m,y}\hat{\boldsymbol{y}} + m_{m,z}\hat{\boldsymbol{z}}, \tag{4}$$

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 [6], as

$$I_\Sigma = I(0) + I(\pi) = -\frac{4\pi R Y_0 G_m}{1+2Y_0 Z_L} m_{m,z}, \tag{5}$$

$$I_\Delta = I(0) - I(\pi) = -\frac{2\pi R Y_1 G_e}{1+2Y_1 Z_L} m_{e,y}, \tag{6}$$

where

$$G_m = \frac{\eta}{4\pi}\left(\frac{k^2}{R} - \frac{jk}{R^2}\right) e^{-jkR}, \tag{7}$$

$$G_e = -\frac{\eta}{4\pi}\left(\frac{jk}{R} + \frac{1}{R^2} + \frac{1}{jkR^3}\right) e^{-jkR}. \tag{8}$$

2.1.2 Full Electromagnetic Vector Sensor

Using three mutually orthogonal loops, and ignoring scattering and mutual impedance, allows for the detection of all six independent electromagnetic components (i.e. three electric intensity components and three magnetic intensity components.) The orientation of the loops are with reference to the normal vector, following the right-hand rule with respect to the loop current. For example, $I_z(\phi)$ is the current through a loop in the xy-plane with the current circling the positive z-axis in a counter-clockwise direction. The orientation of the antipodal ports will be referenced through a unit vector pointing to the port 1 location. For example, $\boldsymbol{p}_{z,1} = [1,0,0]^T$ denotes that port 1 of the z-directed loop is along the x-axis.

For centrally located moment sources,

$$\boldsymbol{m}_m = -\frac{(1+2Y_0 Z_L)}{4\pi b G_m Y_0} \boldsymbol{I}_\Sigma, \tag{9}$$

$$\boldsymbol{m}_e = -\frac{(1+2Y_1 Z_L)}{2\pi b G_e Y_1} \boldsymbol{P}_\pi \boldsymbol{I}_\Delta. \tag{10}$$

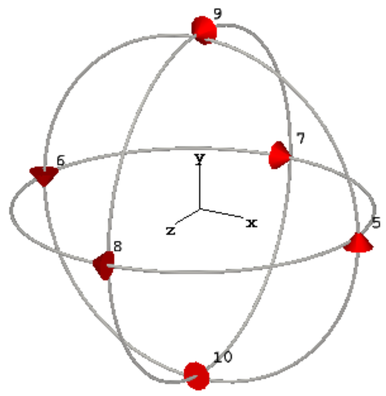
where $\boldsymbol{P}_\pi$ is the permutation matrix where the i^{th}rows contain the port 1 unit vector of the i^{th} Cartesian coordinate directed loop,

$$\boldsymbol{P}_\pi = \begin{bmatrix} \boldsymbol{p}_{x,1}^T \\ \boldsymbol{p}_{y,1}^T \\ \boldsymbol{p}_{z,1}^T \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \tag{11}$$

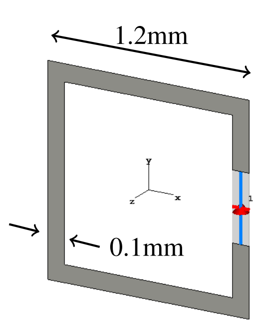
$$\boldsymbol{I}_\Sigma = (I_x^{(1)} + I_x^{(2)})\hat{\boldsymbol{x}} + (I_y^{(1)} + I_y^{(2)})\hat{\boldsymbol{y}} + (I_z^{(1)} + I_z^{(2)})\hat{\boldsymbol{z}}, \tag{12}$$

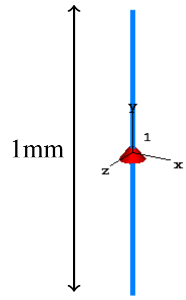
$$\boldsymbol{I}_\Delta = (I_x^{(1)} - I_x^{(2)})\hat{\boldsymbol{x}} + (I_y^{(1)} - I_y^{(2)})\hat{\boldsymbol{y}} + (I_z^{(1)} - I_z^{(2)})\hat{\boldsymbol{z}}, \tag{13}$$

and $I_i^{(1)}$ and $I_i^{(2)}$ are the currents in port 1 and port 2 of the i-directed loop, respectively.



(a) TLAS model





(b) Magnetic dipole model **(c)** Electric dipole model

Figure 1. (a) Simulation model used to compare the response of a TLAS in isolation versus in the presence of a ground plane. The loop radii were $R = 0.5$m and the loop wire radii $r_w = 1cm$. For each case, the loops were offset so that they were separated by a loop wire radius r_w. The source was either a centrally located electric or magnetic dipole. (b) Electric dipole model. (c) Magnetic dipole model.

3 Experimental Results

TLAS ground plane proximity effects were investigated using CST Microwave Studio time-domain simulations [7]. A TLAS, with either a centrally located electric or magnetic dipole moment source, was simulated in freespace with open boundaries and compared against the TLAS response with the presence of a Perfect Electric Conductor (PEC) ground plane at one of the Cartesian boundaries. The ground plane distance from the TLAS was varied, and the experiment was repeated with the PEC ground located at a different Cartesian boundary. The simulation model can be seen in Fig. 1. The z-directed loop, i.e. the loop within the xy-plane, was used for all the comparisons, with a fixed loop wire radius of 1cm and the loop radius $R = 0.5$m. The port impedances were all $Z_L = 315\Omega$ and the port gaps were fixed at $h = R/50$. The loops were offset such that their separation distance from the other loops were a loop wire radius.

3.1 Dipole Moment Sources

The dual-loaded loop currents were simulated using a centrally located electrically small dipole source, with and without the presence of a PEC ground plane. The centrally located source was either a small magnetic or electric dipole, each modelled using CST's discrete current source ports. For each dipole source, the ground plane separation distance to the TLAS was varied and compared against the response with open boundaries.

3.1.1 Magnetic Dipole Moment

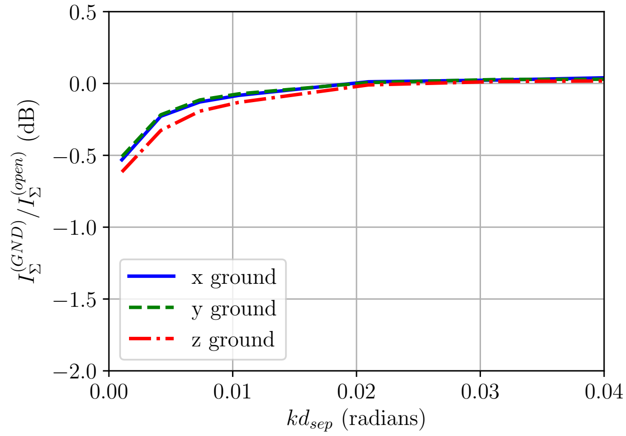
The electrically small magnetic dipole moment source, as shown in Fig. 1b, was modelled as a square loop with 1.2mm long edges and width of 0.1mm. The magnetic dipole was located at the center of the z-directed loop and excited with a 1A discrete current port. Figure 2 shows the difference in the response of a TLAS to a magnetic dipole when a PEC ground plane is present compared to when the boundaries are open. Figure 2a shows that the presence of the ground plane has little impact (< 0.6dB) on the detection of a centrally located magnetic dipole moment. Figure 2b shows that discrimination margin decreases as the ground plane separation distance decreases. A small discrimination margin leads to a decreased ability to discern between magnetic and electric dipole moment sources. TLASs are typically used over a frequency range where the loops are electrically small (i.e. $kb < 0.1$), so at $kb = 0.1$ the discrimination margin can be seen to degrade by 26dB in the worst case ground plane orientation (i.e. perpendicular to the x-axis, from 64dB to 38dB).

3.1.2 Electric Dipole Moment

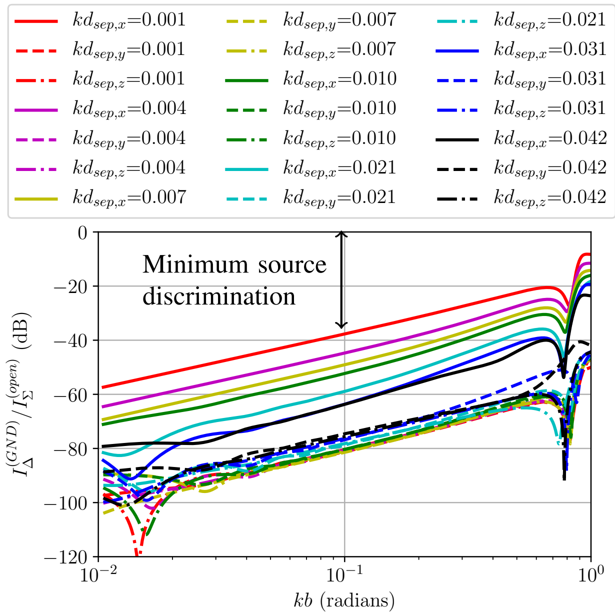
The electrically small electric dipole moment was modelled as a 1mm long constant 1A current source, located at the center of the z-directed loop. Figure 3 shows the difference in the response of TLAS to the electric dipole in the presence of a PEC ground plane compared to open boundaries. Figure 3a shows that the presence of the ground plane has little impact (< 0.8dB) on the detection of a centrally located electric dipole moment. Again, the main impact on the performance from the proximity of the ground plane is the source discrimination margin. Figure 3b shows that discrimination margin decreases as the ground plane separation distance decreases. At $kb = 0.1$, the discrimination margin can be seen to degrade by 27dB in the worst case ground plane orientation (i.e. perpendicular to the x-axis, from 59dB to 32dB).

4 Conclusion

In practical applications, one or more ground planes will be in proximity of deployed TLASs. The theory of TLASs assumes that the performance of each loops is that of a loop in isolation. This paper investigated the effects of nearby

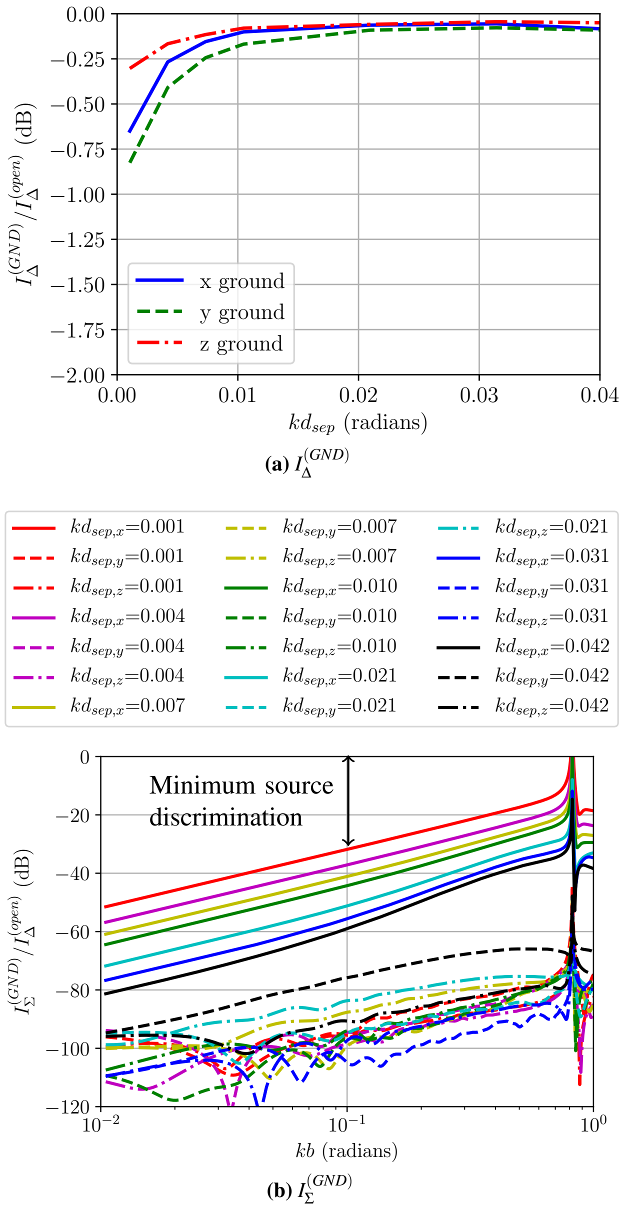


(a) $I_\Sigma^{(GND)}$



(b) $I_\Delta^{(GND)}$

Figure 2. Response on the z-directed loop within a TLAS to a centrally located z-directed magnetic dipole source. (a) The current $I_\Sigma^{(GND)}$ when PEC ground planes located a distance d_{sep} from the TLAS normalized to the current response of the TLAS with open boundaries, $I_\Sigma^{(open)}$. The ground planes were either perpendicular to the x, y, and z-axis. (b) The current $I_\Delta^{(GND)}$ when PEC ground planes located a distance d_{sep} from the TLAS normalized to the $I_\Sigma^{(open)}$ current response of the TLAS with open boundaries. The ground planes were either perpendicular to the x, y, and z-axis. As shown, $I_\Delta^{(GND)}$ increases relative to $I_\Sigma^{(open)}$ (within 26dB at $kb = 0.1$) for magnetic dipole sources when the PEC ground plane is perpendicular to the x-axis and is close to the TLAS.



(a) $I_\Delta^{(GND)}$

(b) $I_\Sigma^{(GND)}$

Figure 3. Response on the z-directed loop within a TLAS to a centrally located y-directed electric dipole source. (a) The current $I_\Delta^{(GND)}$ when PEC ground planes located a distance d_{sep} from the TLAS normalized to the current response of the TLAS with open boundaries, $I_\Delta^{(open)}$. The ground planes were either perpendicular to the x, y, and z-axis. (b) The current $I_\Sigma^{(GND)}$ when PEC ground planes located a distance d_{sep} from the TLAS normalized to the $I_\Delta^{(open)}$ current response of the TLAS with open boundaries. The ground planes were either perpendicular to the x, y, and z-axis. As shown, $I_\Sigma^{(GND)}$ can become appreciable to $I_\Delta^{(open)}$ (within 27dB at $kb = 0.1$) for electric dipole sources when the PEC ground plane is perpendicular to the x-axis and is close to the TLAS.

PEC ground plane on the performance of TLASs when receiving from centrally located electric or magnetic dipole sources. Simulation results show that nearby ground planes have little impact on the performance of TLASs. The current responses in the presence of a ground are shown to be within 1dB from the response with open boundaries. However, the source discrimination can degrades as the ground plane approaches the TLAS although, even for the worst case orientation, maintains greater than 30dB discrimination.

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