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Considerations on the use of Three-Loop Antenna Systems for Biomedical Applications

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Abstract

Three-loop antenna systems (TLASs) have the ability to simultaneously detect all of the components of the electromagnetic field. Since being invented, TLASs have been deployed in a limited scope of applications, with electromagnetic compatibility testing being the primary use. We show that TLASs have a frequency independent response to centrally located electric dipole moment sources and propose that TLASs offer unique advantages compared to micro-probes when sensing electrically small sources. We suggest two specific applications where TLASs could be used: sensing electromagnetic emissions from microorganisms and electroencephalography screening.

1 Background and Introduction

A dual-loaded loop is a well known electromagnetic sensor capable of simultaneously detecting a component from each of the electric and magnetic field vectors [1]. 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.) Originally, the TLAS was proposed for magnetic field measurements for Electromagnetic Compatibility (EMC) measurements [2]. Kanda and Hill showed that TLASs are also capable of detecting linearly polarized plane waves and the total electric and magnetic dipole moment vectors, located at the centre of the loops [3]. Although TLAS are capable of simultaneously detecting the total electric and magnetic field vectors, and hence energy density, little attention has been given to exploiting this capability, with the exception of a vector sensor for direction finding [4]. Since being invented, TLASs have been primarily used for EMC testing of large consumer devices [5].

This paper summarizes TLASs responses to plane waves and electric and magnetic dipole moments and introduces notation for the total measured vector response. The TLAS response is shown to be frequency independent to centrally located electric dipole moments. This finding has ramifications for applications using electrically small probes to detect signals from electrically smaller sources. Finally, we discuss the state of the art and our progress on two non-traditional applications of TLASs: (i) detecting emissions from microorganisms, and (ii) electroencephalography (EEG) screening.

2 Theory

Throughout this paper complex notation is used and the time harmonic factor, $e^{j\omega t}$, has been suppressed.

2.1 Review of a Single Loop Electric and Magnetic-field Sensor

The sum and difference currents through the loads of an electrically small loop can be expressed in terms of the Fourier series coefficients of the tangential electric field on the loop [6],

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

where b is the loop radius, Z_L is the load impedance of the ports, Y_1 is the admittance of the $n=1$ current mode, and f_i is the Fourier series i^{th} coefficient of the Fourier series expansion of the tangential electric field.

The sum of the port currents is

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

where Y_0 is the admittance of the $n=0$ current mode and f_0 is the $n=0$ Fourier series coefficient of the Fourier series expansion of the tangential electric field.

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 along the x-axis, the sum and difference currents are related to components of the electric and magnetic intensities [6],

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

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

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 [6], as

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

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

where

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

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

2.2 Full Electromagnetic Vector Sensor

By 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, $\boldsymbol{p}_{z,1} = \left[1,0,0\right]^T$ denotes that port 1 of the z-directed loop is along the x-axis.

From (3) and (4) it follows that,

$$\boldsymbol{H} = \frac{j(1 + 2Y_0 Z_L)}{2\pi k b^2 \eta Y_0} \boldsymbol{I_\Sigma}, \tag{11}$$

$$\boldsymbol{E} = -\frac{(1 + 2Y_1 Z_L)}{2\pi b Y_1} \boldsymbol{P_\pi} \boldsymbol{I_\Delta}, \tag{12}$$

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,

$$\boldsymbol{P_\pi} = \begin{bmatrix} \boldsymbol{p}_{x,1}^T \\ \boldsymbol{p}_{y,1}^T \\ \boldsymbol{p}_{z,1}^T \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \tag{13}$$

$$\boldsymbol{I_\Sigma} = (I_x^{(1)} + I_x^{(2)})\hat{\boldsymbol{x}} + (I_y^{(1)} + I_y^{(2)})\hat{\boldsymbol{y}} + (I_z^{(1)} + I_z^{(2)})\hat{\boldsymbol{z}}, \tag{14}$$

$$\boldsymbol{I_\Delta} = (I_x^{(1)} - I_x^{(2)})\hat{\boldsymbol{x}} + (I_y^{(1)} - I_y^{(2)})\hat{\boldsymbol{y}} + (I_z^{(1)} - I_z^{(2)})\hat{\boldsymbol{z}}, \tag{15}$$

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

For centrally located moment sources,

$$\boldsymbol{m}_m = -\frac{(1 + 2Y_0 Z_L)}{4\pi b G_m Y_0} \boldsymbol{I_\Sigma}, \tag{16}$$

$$\boldsymbol{m}_e = -\frac{(1 + 2Y_1 Z_L)}{2\pi b G_e Y_1} \boldsymbol{P_\pi} \boldsymbol{I_\Delta}. \tag{17}$$

For electrically small loops (*i.e.* $kb \ll 1$,) the third term in (10) dominates and we find the surprising result that the response of the TLAS to electric dipole moment sources is independent of frequency,

$$\boldsymbol{P_\pi} \boldsymbol{I_\Delta} = -\frac{2\pi b Y_1}{(1 + 2Y_1 Z_L)} G_e \boldsymbol{m}_e, \tag{18}$$

$$\approx -\frac{2\pi b Y_1}{(1 + 2Y_1 Z_L)} \frac{j\eta}{4\pi k b^3} \boldsymbol{m}_e, \tag{19}$$

$$\approx -\frac{2\pi b \frac{2jkb}{\eta\left(\ln\frac{8b}{a} - 2\right)}}{\left(1 + 2\frac{2jkb}{\eta\left(\ln\frac{8b}{a} - 2\right)} Z_L\right)} \frac{j\eta}{4\pi k b^3} \boldsymbol{m}_e, \tag{20}$$

$$\approx \frac{1}{b \ln\frac{8b}{a}} \boldsymbol{m}_e, \tag{21}$$

where the electrically small loop approximations are used for the admittance Y_1 [7].

This can have significant ramifications for applications that detect electrically small sources using electrically small probes. If one uses a micro-probe to detect a small source, there will be significant impedance mismatch and the probe will have to be precisely positioned very close to the source to detect a component of the electric dipole moment that is polarization-matched to the micro-probe, with highly variable coupling. Using a much larger TLAS will suffer less impedance mismatch, and can detect the full dipole moment vector, independent of dipole-to-sensor orientation.

3 Discussion

3.1 TLAS as a Microorganism Sensor

Although challenging to measure, electromagnetic emissions from microorganisms have been reported from direct measurement since the 1980s [8]. One hypothesized source of these emissions is from microtubules (MTs.) Investigations into EM emissions from MTs has seen an increase

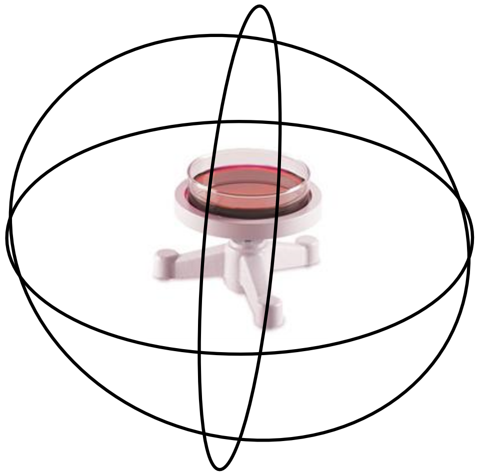

Figure 1. Sketch of TLAS with a Petri dish.

in attention in recent years, specifically from some researchers investigating eletromagnetic emissions from eukaryotic cells [9]. MTs are composed of subunits having a high electric dipole moment of over $10^{-26}Cm$ [10]. Given there are several hundreds of MTs in a cell (depending on the cell type,) and that cells vibrate due to various causes, MT should emit EM emissions. Studies investigating the vibrational modes and associated radiation from microtubes has sugguested that EM emissions may span broad spectral range from kHz to GHz [11, 12]. The main problem with sensing microorganism EM emissions is that the power levels are extremely low, typically at an overall power level on the order of 10^{-18} to $10^{-20}W$ [13]. Such low power levels have led researchers to use micro-probes when sensing EM emissions from microorganism, with the micro-probe tips placed directly on either side of the specimen under test. Micro-probing microorganisms is a difficult task that requires accurate confinement of the specimen, and will suffer from likely polarization mismatch and poor coupling. Descriptions of the measurement systems and details are scant, and similarly for confirming measurements, in the open literature. As an alternative to microprobing, we are proposing to use a TLAS for detecting emissions from microorganisms. A TLAS does not require any specimen confinement and senses the complete electric and magnetic dipole moment vector, independent of dipole-to-sensor orientation. The relative performance of a microprobe compared to a TLAS is unknown. However, in addition to the frequency independent response to electric moments that was shown above, the impedance mismatch and polarization mismatch of the TLAS will be better. These performance advantages, coupled with the greatly simplified measurement process, provide an impetus to design a low-signal level TLAS for microorganism sensing.

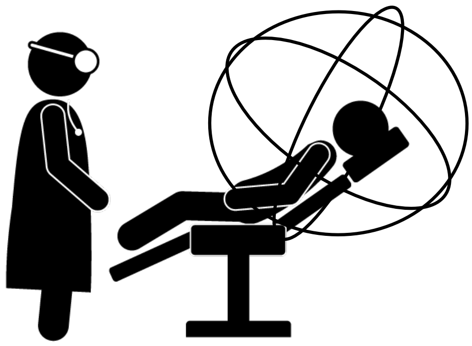

Figure 2. Sketch of TLAS with a hospital patient (the TLAS will likely be larger for convenience.)

3.2 Electroencephalography Pre-screening

The process of recording an EEG requires a skilled technician to place electrodes at precise locations on the head. Signals from the brain, in the Extremely Low Frequency range, are recorded for a range of times. With a typical recording time of 20 minutes, the process, with preparation and cleaning, has a duration of about an hour. Once completed, a neurologist needs to schedule time to review the record. Often the assessments are done in bulk session, waiting until a sufficiently large number of records are ready for review. This tends to lead to significant delays for the test results. Significant time and cost savings, could be achieved by pre-screening patients using a TLAS. The patient could sit at the centre of a relatively large TLAS and the recorded signals could be analysed using deep-learning techniques to screen the patients. For example, it is likely that generalized epileptiform or generalized slowing could be easily identifiable using a TLAS.

4 Conclusion

The three-loop antenna systems is an underutilized electromagnetic sensor. Often limited to EMC testing applications, we propose two application domains where a TLAS could augment current testing capabilities: sensing electromagnetic emissions from microorganisms and prescreening EEG patients. It was shown that a TLAS has a frequency independent response to centrally located electric dipole moments. As such, a TLAS provides a much more convenient means of sensing an electrically small dipole source with an electrically small sensor. A TLAS offers superior performance compared to a micro-probe as the coupling is independent of sensor-to-source orientation and it detects the full moment vector, as compared to a microprobe that will suffer from polarization mismatch and potential poor coupling. The elimination of accurate sensor placement offers significant time savings. For these reasons, further investigations will be performed in using a TLAS system for these applications.

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References

[1] H. Whiteside and R.W.P. King, "The loop antenna as a probe," *IEEE Transactions on Antennas and Propagation*, vol. 12, no. 3, pp. 291–297, May 1964.

[2] J. Bergervoet and H. van Veen, "A large loop antenna for magnetic field measurements," in *The 8th International Zurich Svmposium and Technical Exhibition on Electromaenetic Compatibility*, Zurich, Mar 1989, pp. 29–34.

[3] M. Kanda and D. A. Hill, "A three-loop method for determining the radiation characteristics of an electrically small source," *IEEE Transactions on Electromagnetic Compatibility*, vol. 34, no. 1, pp. 1–3, Feb 1992.

[4] J. H. Meloling, J. W. Rockway, M. P. Daly, A. R. Monges, J. C. Allen, W. R. Nielsen, P. M. McGinnis, R. B. Thompson, and N. A. Mozaffar, "A vector-sensing antenna system: A high-frequency, vector-sensing array based on the two-port loop antenna element." *IEEE Antennas and Propagation Magazine*, vol. 58, no. 6, pp. 57–63, Dec 2016.

[5] D. R. Novotny, K. D. Masterson, and M. Kanda, "An optically linked three-loop antenna system for determining the radiation characteristics of an electrically small source," in *1993 International Symposium on Electromagnetic Compatibility*, Aug 1993, pp. 300–305.

[6] C. G. Hynes and R. G. Vaughan, "Electromagnetic loop sensor," in *Submitted to URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020.*

[7] M. Kanda, "An electromagnetic near-field sensor for simultaneous electric and magnetic-field measurements," *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-26, no. 3, pp. 102–110, Aug 1984.

[8] M. Cifra, J. Z. Fields, and A. Farhadi, "Electromagnetic cellular interactions," *Progress in Biophysics and Molecular Biology*, vol. 105, no. 3, pp. 223 – 246, 2011.

[9] O. Kučera, D. Havelka, and M. Cifra, "Vibrations of microtubules: Physics that has not met biology yet," *Wave Motion*, vol. 72, pp. 13–22, 2017.

[10] J. Tuszyński, T. Luchko, S. Portet, and J. Dixon, "Anisotropic elastic properties of microtubules," *The European Physical Journal E*, vol. 17, no. 1, pp. 29–35, 2005.

[11] M. Cifra, J. Pokornỳ, D. Havelka, and O. Kučera, "Electric field generated by axial longitudinal vibration modes of microtubule," *BioSystems*, vol. 100, no. 2, pp. 122–131, 2010.

[12] O. Kučera and D. Havelka, "Mechano-electrical vibrations of microtubules—link to subcellular morphology," *Biosystems*, vol. 109, no. 3, pp. 346–355, 2012.

[13] O. Kucera, M. Cifra, and J. Pokornỳ, "Technical aspects of measurement of cellular electromagnetic activity," *European Biophysics Journal*, vol. 39, no. 10, p. 1465, 2010.