Reply to "Comment on 'EM induction in elongated conductors normal to a coastline with application to geomagnetic measurements in Nigeria' by J. Chen, H. W. Dosso, and S. Kang"

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Dr. P. F. Chen (hereafter PFC) has questioned two main differences between the CDK analogue model and his FDM numerical results: 1) The CDK analogue model in-phase V_y fall off rapidly with increasing period, whereas his numerical H_z/H_y do not; 2) The CDK quadrature V_y do not show a reversal, whereas his H_z/H_y do. Upon examining the curves in Fig. 4 carefully, it can be concluded that the CDK quadrature V_y do, in fact, also indicate a reversal. It can clearly be seen from the shape of the CDK curves (dashed line), that with decreasing period each response curve is approaching a reversal, though at a period some what below 1 min, being the lowest period included in the analogue model measurements. The CDK in-phase response curves as well, are each approaching a maximum at periods well below 1 min, and should each reach a maximum at roughly the same period as the corresponding quadrature reversal, being characteristic of the specific location (y) between the conductors. These shifts to longer periods with distance indicated in the CDK results, are similar to those in the PFC (solid line) results which for sites at increasing distances from the major conductor (b), show shifts to longer periods to be roughly $T_c = 2, 3,$ and 8 min at $y = -45, -40,$ and -30 km respectively. With respect to the more rapid fall-off in-phase response with increasing period, as well as the quadrature reversals at lower periods in the CDK 3D results as compared with the PFC results, these are precisely the characteristics that distinguish 3D from 2D responses. The CDK model for the 1–60 min period range is certainly 3D for all but the shortest periods, since for the near-end ($x = 30$ km) traverse the conductor length is definitely too small to satisfy the criteron for a 2D conductor in terms of host conductivity skin depths. Thus, the PFC roughly constant in-phase H_z/H_y over the 1–60 min range appear to show a 2D rather than what should be a 3D response.

Unfortunately, PFC does not include any explanation regarding the numerical grid design, the boundary conditions, or the convergence criteria used in his finite difference numerical model for the high conductivity contrast ($\sim$5000), and the large (1–60 min) period range for which the highly resistive host skin depth changes by nearly a factor of 8.

Did he use air layers above the surface, or did he use a surface boundary condition? If he used air layers, what was the height extent? Did he use the same uniform grids for all periods, or did he change the grids for different periods where appropriate in order to enhance the accuracy? Without stating any convergence criteria, he does state that his iteration did converge, though slowly, but does this necessarily constitute proof that the numerical results are valid? If the differences between the PFC and the CDK results cannot be attributed to numerical inaccuracies in the PFC results due to possible difficulties with grid design, boundary conditions, convergence, etc., then the departure from the observed CDK 3D results might only be attributed to basic differences in V_y and H_z/H_y responses for a 3D structure. Then the question remaining is, why for clearly a 3D model for which the analogue model V_y show a 3D response, do the numerical H_z/H_y show a 2D like response? Addressing this question might have been of interest to a broader readership than the one of attempting to prove the analogue model results to be in error.

Now the question arises as to why the PFC numerical results behave more like those of a 2D model for the CDK 3D model even at the longer periods? Is it perhaps, that the FDM technique encounters difficulties with a large conductivity contrast (5000 used here), as is sometimes experienced in numerical modelling? Has a difficulty already arisen in obtaining the Fig. 2 respnses, since if the dimensions (Fig. 1) are taken to be valid for 2D at 1 min period, then the two response curves in each of Figs. 2a and 2b should be the same. This is not the case for the quadrature results (H_z/H_y and V), since at a short distance from the conductor boundary the FDM 3D responses (dotted lines) over the host are about 40% larger and fall off much more slowly with range than the 2D responses (solid lines). This trend is opposite to that expected, since the end effects of a 3D structure should, if any thing, reduce the magnitude of the responses while increasing the fall-off with range compared with that for a 2D structure. This significant discrepency in the Fig. 2 results would appear to cast doubt on the validity of the PFC H_z/H_y responses for the CDK 3D model.

The relatively constant FDM (Figs. 3 and 4) in-phase H_z/H_y are very similar to the 2D-like responses seen in the lower period range (Figs. 2 and 3) in the Chen and Dosso

(1997) analogue model study of a central traverse over a 500 km length conductor at various distances from a straight ocean coastline. As in the case for the CDK model, the conductive basement was at a 200 km depth. In this work, the T_c was between 2 and 3 min at the site nearest the major conductor (ocean) and was shifted to longer periods at more distant sites. Thus, the PFC (Figs. 3 and 4) relatively constant in-phase responses, as well as the T_c values, are very similar to those in the Chen and Dosso (1997) study. It should be emphasised, that this observed similarity is contrary to what should be the case, since the responses at short periods for the central traverse over the 500 km length conductor are those of a 2D structure, while the FDM responses for the near-end ($x = 30$ km) traverse in the CDK model should be those of a 3D structure. In a more recent work, Dosso *et al.* (1999) carried out an analogue model study of an elongated conductor for a range of conductor lengths, depths of burial, and conductive basement depths for both central and near-end traverses. Both T_c shifts to shorter periods and more rapid response fall-off with period were seen for decreasing conductor lengths (which effectively transformed the conductor into a more 3D-like sructure at a given period). These analogue model results all cast further doubt on the validity of the FDM technique for providing the correct responses for complex 3D structures.

In numerical studies, an example of relatively constant in-phase responses (similar to those shown in the PFC results in Fig. 4) over a moderate period range can be found in the Agarwal and Dosso (1990) 2D numerical study of a conductive plate for two conductive basement depths. In addition, a recent 3D numerical study by Agarwal and Dosso (1999) of a conductive block further confirms both the more rapid response fall-off with period, as well as the lower T_c for 3D, as compared with those for 2D structures. This latter numerical study uses the finite difference staggered grid algorithm of Agarwal *et al.* (1996) based on the fixed grid 3D numerical algorithm of Weaver *et al.* (1999). Both algorithms use surface boundary conditions and handle high conductivity contrasts successfully. These two numerical studies, as well as the analogue model studies discussed in the preceeding paragraphs, support the view that the PFC numerical FDM H_z/H_y results do not follow the expected general behaviour of the 3D responses. Perhaps, the Fig. 7 model in the CDK (1997) work would be more appropriate for testing the FDM technique, since both V_x and V_y are provided for what definitely is a 3D structure.

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