1 # Modeling of terrain effect in magnetotelluric data from Garhwal Himalaya Region

3 Suman Saini[1*], Deepak Kumar Tyagi[2], Sushil kumar[3], Rajeev Sehrawat[1**]

4 [1]Department of Physics, M. M. Engineering College, Maharishi Markandeshwar (Deemed to be)
5 University, Mullana-Ambala, Haryana, India 133207

6 Corresponding Author- Rajeev Sehrawat[1**]

7  **Email: rajeev.sehrawat@mmumullana.org

8 *Email: sumanabcd12@gmail.com

9 [2]Department of Physics, Krishnan College of Science and IT,M.J.P. Rohilkhand University, Bijnor,
10 Uttar Pradesh,India-246701

11 [3]Department of Geophysics, Kurukshetra University, Kurukshetra, India-136119

## ABSTRACT

13 Magnetotelluric methods (MT) are passive geophysical techniques based on time variations of the

14 geoelectric and geomagnetic field in order to measure the electrical resistivity of surface layer. It is

15 most effective geophysical techniques to study the deep structure of the Earth's crust, particularly in

16 steep terrain like the Garhwal Himalaya region. The MT responses are distorted as a result of the

17 undulated/rugged terrain. Such responses, if not corrected, can lead to a misinterpretation of MT data

18 for the geoelectrical structures. In this study, two different correction procedures were used to

19 compute the topography distortion for the synthetic model of Garhwal Himalaya region from Roorkee

20 to Gangotri section. A finite difference algorithm was used to compute MT responses (apparent

21 resistivity and phase) for the irregular terrain. The accuracy of the terrain correction procedures was

22 checked on results published in the literature on different topography models at various periods. The

23 relative errors between two terrain correction procedures were calculated with respect to flat earth and

24 were very less or almost zero for most of the sites along the Roorkee to Gangotri profile except at the

25 foothill where the error was high at lower periods. The similar topography response, terrain corrected

26  responses TCR1 and TCR2 responses concluded that there is no need for topography correction along

27  Roorkee-Gangotri Profile because the slope angle is less than one degree.

28  **Keyword**s: Magnetotelluric, Topography correction procedures, Himalaya region

## 1. INTRODUCTION

30  The magnetotelluric (MT) method was first explored by Tikhonov (1950) and Cagniard (1953) and

31  was used to analyse the time-varying measured components of earth's natural time-varying electric

32  and magnetic fields to determine the shallow layers of the Earth. MT technique has been successfully

33  used to explore a variety of earth resources, including oil, gas, mineral, and geothermal energy (Zhang

34  et al., 2014; Patro et al., 2017; Mohan et al., 2017).  The MT method is effective for analysing deep

35  crystal structures in challenging undulating terrains, such as the Himalayan region as compared to the

36  seismic method (Tyagi , 2007; Israil et al., 2008, 2016; Pavan Kumar et al., 2014; Patro and

37  Harinarayana, 2009; Kumar et al., 2018, 2022; Xiong-Bin, 2020; Dharmendra Kumar et al., 2021;

38  Konda et al., 2023). Topography affects both the electric field and magnetic field components due to

39  undulating topographical features like hills and valleys, which distort the current lines (Wannamaker

40  et al., 1986; Michel Choutraus et al., 1988; Changhong et al., 2018; Kumar et al., 2018, 2022).

41  Therefore, the MT response functions impedance and apparent resistivity get distorted when the MT

42  sites are on or near the top of the hill or close to the valley.

43  Analytical and numerical techniques have been used to measure the topography distortion effect from

44  MT data. Analytical techniques based on conformal mapping were used by Thayer (1975),

45  Harinarayana and Sarma (1982). The 2D numerical techniques have been used for different type

46  terrain geometries to remove topography effects from the data.  The analogue, analytic, and numerical

47  solution methods were used to study the analogue model (Wescott and Hessler, 1962; Faradzhev et al.,

48  1972).Various two-dimensional (2D) numerical techniques have been used for the numerical

49  treatment of the topographic effects like networking analogy (Ku et al., 1973; NgCo, 1980) and

50  Rayleigh scattering numerical modeling techniques (Reddig and Jiracek, 1984; Jiracek et al., 1989),

51  finite element method (Wannamaker Stodt and Rijo, 1986; Frankle et al., 2007) and finite difference

52  method (Josef Pek and Tomas Verner, 1996; Yutaka Sasaki, 2003 and Tyagi et al., 2007). The

53  distortions in MT data due to topography and near-surface inhomogeneities have been observed by

54  many researchers (Michel Choutraus et al., 1988;Jiracek, 1990; Vozoff, 1991). The distortion tensor

55  stripping-off technique has been used to reduce the topographic effect and to remove the distortion

56  due to the near-surface heterogeneity (Larsen, 1971). The analogue, analytic, and numerical solution

57  methods were used to study the analogue model (Wescott and Hessler, 1962; Faradzhev et al.,

58  1972).Various two-dimensional (2D) numerical techniques have been used for the numerical

59  treatment of the topographic effects like networking analogy (Ku et al., 1973; NgCo, 1980) and

60  Rayleigh scattering numerical modeling techniques (Jiracek Redding and Kojima, 1989) and finite

61  element method (Wannamaker Stodt and Rijo, 1986; Frankle et al., 2007). In 2D, the topography

62  effect is galvanic in Transverse Magnetic (TM) mode and inductive in Transverse Electric (TE) mode,

63  hence more distortion in TM mode than TE mode (Gurer and Ilikisik, 1997; Kumar et al., 2014;

64  Kumar et al., 2018, 22).

65  In this study, modified 2D forward and inversion modeling code EM2INV (Rastogi, 1997) based on

66  the finite difference method were used to compute MT forward modeling responses over flat earth and

67  topographic surface. Two different terrain correction procedures have been used in this study: first

68  correction procedure was adopted from Chouteau and Bouchard (1988) and the second was adopted

69  from Nam et al., (2008) to compute the topography distortion for the synthetic model of

70  GarhwalHimalayan region (Roorkee-Gangotri section). The results of both terrain correction

71  procedures have been compared with the model used by Chouteau and Bouchard (1988).

## 2. METHODOLOGY

73  The topography correction to the MT data has been applied by two different techniques. The first

74  technique was introduced by Chouteau and Bouchard (1988) to estimate the distortion tensor and

75  correction of MT data before inversion of MT data. In the second approach, the distortion tensor

76  stripping-off technique was used to remove the distortion from the MT data (Larsen, 1977 and Nam et

77  al., 2008). Two correction procedures, first adopted by Chouteau and Bouchard (1988) and second by

78  Nam et al., (2008), were used to correct the MT data.

### 2.1 Terrain correction procedure 1 (TCP1):-

80  The computational algorithm for 2D forward modeling has been used to account for irregular terrain.

81  The distortion tensor for the topographic effect was calculated using the technique adopted by

82  Chouteau and Bouchard (1988). Based on the assumption that the topography distorted subsurface

83  field can be approximated by multiplying the distortion tensor by the subsurface field for a flat earth

84  given by:

85  $$\widetilde{E_D} = D\widetilde{E_N} \tag{1}$$

86  where $\widetilde{E_D}$ and $\widetilde{E_N}$ are the distorted and normal electric field matrices with elements $E(f,r)_D$ and

87  $E(f,r)_N$ respectively. $\widetilde{D}$ is the distortion tensor with elements $D(f,r)$, where $f$ is frequency and $r$ is

88  the measuring site position. In case of 2D problem in TM mode and x-axis is the direction of strike,

89  equation (1) can be written as

90  $$E_{XD}(f,r) = D_{XX}(f,r)E_{XN}(f,r) \tag{2}$$

91    The impedance tensor can be calculated by dividing equation (2) by the magnetic field $H_Y$.

92    $Z_D(f,x) = D(f,x)Z_N(f,x)$ (3)

93    where $Z_N(f,x)$ and $Z_D(f,x)$ are respectively the normal (flat earth) impedance and distortion

94    impedance. The complex coefficients $D(f,x)$ are distortion coefficients that should just reflect

95    topography effect. The distortion coefficients are calculated by normalizing the impedances $Z_t(f,x)$

96    computed over topographic model above a homogeneous medium with the half-space impedance.

97    Thus, the corrected impedance over flat earth can be calculated by taking the following ratio of the

98    observed impedances, $Z_D(f,x)$, over irregular topography to the distortion coefficients $D(f,x)$:

99    $Z_C(f,x) = Z_D(f,x)/D(f,x)$ (4)

100   where $Z_C(f,x)$ is terrain-corrected impedance.

101   **2.2 Terrain correction procedure 2 (TCP2) :-**

102   In this correction procedure, the MT data was corrected using the technique adopted by Nam et al.,

103   (2008). Larsen (1977) introduced the distortion tensor stripping-off technique, in which the

104   undistorted impedance tensor can be calculated using a linear relationship between the distorted and

105   undistorted impedance tensor, and topography distorted MT data can be corrected by computing the

106   distortion tensor. The undistorted impedance tensor is linearly related to the distorted impedance

107   tensor as:

108   $Z^D = D^Z \cdot Z^U$ (5)

109   where $Z^D$ is the distortion impedance tensor, $D^Z$ is distortion tensor and $Z^U$ is the undistorted

110   impedance tensor respectively. The distortion tensor can be calculated from the relation between the

111     impedance tensor for a homogeneous medium with topography earth surface ($Z^t$), and that with the

112     flat earth surface ($Z^h$) as

113     $Z^t = D^Z \cdot Z^h$                                                      (6)

114     In case of 2D, $Z_{xx}^h = Z_{yy}^h = (0,0)$ and $Z_{xy}^h \neq -Z_{yx}^h$, the inhomogeneous earth distortion tensor,

115     equations (5) and (6) can be rewritten in matrix form as

116    
$$\begin{bmatrix} 0 & Z_{xy}^D \\ Z_{yx}^D & 0 \end{bmatrix} = \begin{bmatrix} 0 & D_{xy}^Z \\ D_{yx}^Z & 0 \end{bmatrix} \begin{bmatrix} 0 & Z_{xy}^U \\ Z_{yx}^U & 0 \end{bmatrix}$$
      (7)

117     and

118    
$$\begin{bmatrix} 0 & Z_{xy}^t \\ Z_{yx}^t & 0 \end{bmatrix} = \begin{bmatrix} 0 & D_{xy}^Z \\ D_{yx}^Z & 0 \end{bmatrix} \begin{bmatrix} 0 & Z_{xy}^h \\ Z_{yx}^h & 0 \end{bmatrix}$$
      (8)

119     So

120    
$$\begin{bmatrix} 0 & D_{xy}^Z \\ D_{yx}^Z & 0 \end{bmatrix} = \begin{bmatrix} 0 & Z_{xy}^t \\ Z_{yx}^t & 0 \end{bmatrix} \begin{bmatrix} 0 & Z_{xy}^h \\ Z_{yx}^h & 0 \end{bmatrix}^{-1}$$
      (9)

121    
$$\begin{bmatrix} 0 & D_{xy}^Z \\ D_{yx}^Z & 0 \end{bmatrix} = \begin{bmatrix} (Z_{xy}^t)/(Z_{xy}^h) & 0 \\ 0 & (-Z_{yx}^t)/(Z_{yx}^h) \end{bmatrix}$$
      (10)

122     Substituting equation (10) in equation (7)

123    
$$\begin{bmatrix} 0 & Z_{xy}^D \\ Z_{yx}^D & 0 \end{bmatrix} = \begin{bmatrix} (Z_{xy}^t)/(Z_{xy}^h) & 0 \\ 0 & (-Z_{yx}^t)/(Z_{yx}^h) \end{bmatrix} \begin{bmatrix} 0 & Z_{xy}^U \\ Z_{yx}^U & 0 \end{bmatrix}$$
      (11)

124     The undistorted or corrected impedance tensor component can be obtained as

125     So

126     $Z_{xy}^U = (Z_{xy}^h Z_{xy}^D)/(Z_{xy}^t)$                                                (12)

127     $Z_{yx}^U = (Z_{yx}^h Z_{yx}^D)/(Z_{yx}^t)$                                                (13)

## 3. TESTING THE CORRECTION PROCEDURES:

In this study, we replicated the model of Chouteau and Bouchard (1988). A 2D topographic homogeneous model of 500 Ω·m half-space with a resistive block of 10 kΩ·m having a thickness of 1 km was embedded in the model from surface relief (Figure 1). The MT responses for the model have been computed with and without topography. The terrain correction procedures (TCP1 & TCP2) have been applied to the model responses at a particular period of 0.1 second (sec) and validated over the inhomogeneous model of Chouteau and Bouchard (1988). The two topography corrected responses were analysedat nine different sites (denoted by A, B, C, D, E, F, G, H& I) as shown in Figure 1 at six distinct time periods (0.001 sec, 0.01 sec, 0.1 sec, 1 sec, 10 sec, and 100 sec).In 2D the topography effect is galvanic in TM mode and inductive in TE mode. Therefore, the comparison of TM component of flat earth response (FER), topographic response (TR) and two terrain correction responses (TCR1 and TCR2) were shown in Figure2. It is concluded from the Figure 2 that the TCR1 and TCR2 are very similar to the FER at particular period of 0.1 sec, but not similar to the TR, which shows a good agreement of published result of Chouteau and Bouchard (1988).
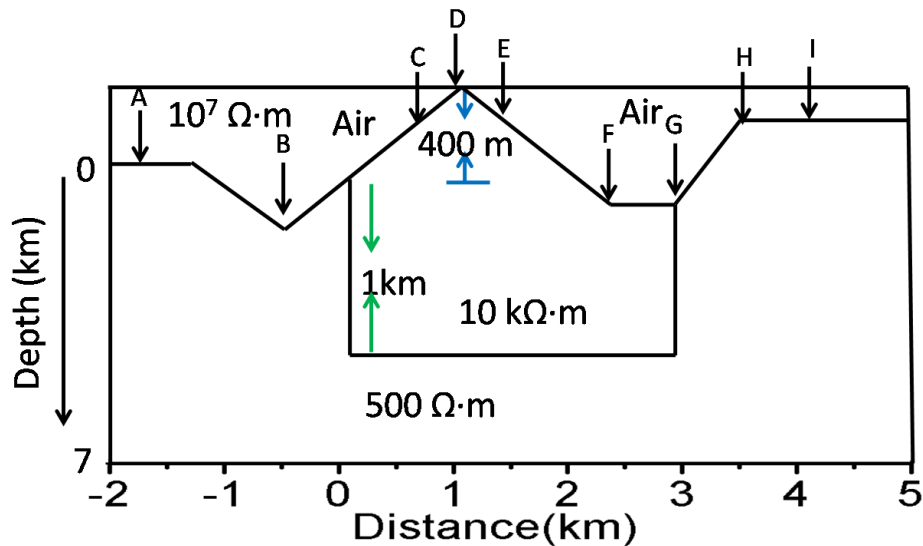
**Figure1:** Topographic model of 500 Ω·m half-space with a resistive body of 10 kΩ·m was embedded from the surface relief (Chouteau and Bouchard, 1988).
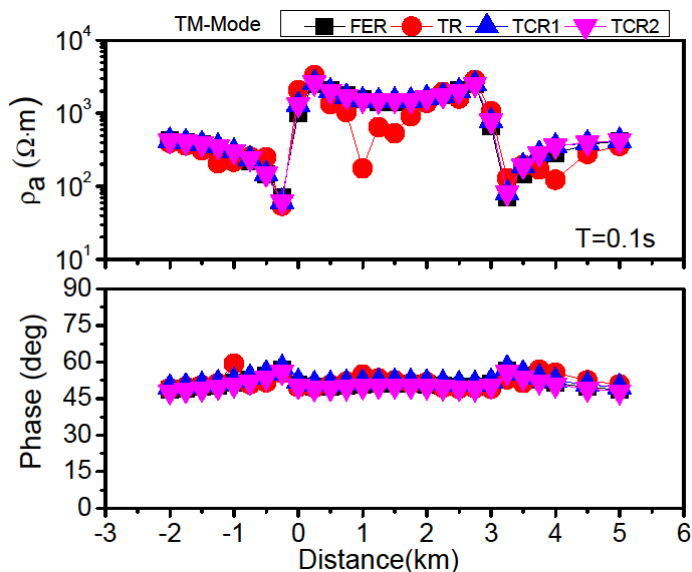
**Figure2:** Comparison of TM component of flat earth response (FER), topographic response (TR) and two terrain correction responses (TCR1 and TCR2) at 0.1 sec.

Figure3 showed that the topography distortions are large for higher period in apparent resistivity component only, which shows the galvanic nature of the topography distortions. The terrain corrected responses (TCR1 and TCR2) in Figure 3 are almost similar to flat earth responses (FER) at six periods (0.001 sec, 0.01 sec, 0.1 sec, 1 sec, 10 sec, and 100 sec respectively). Relative errors were also calculated to check the accuracy of the terrain correction responses (TCR1 and TCR2) with flat earth responses at these periods. The relative error between the FER and TCR1 and TCR2 were very small at all these periods except at site D only at lower periods (because of 10 kΩ·m resistive body) as shown in Figure4. This shows the accuracy of the correction procedures.

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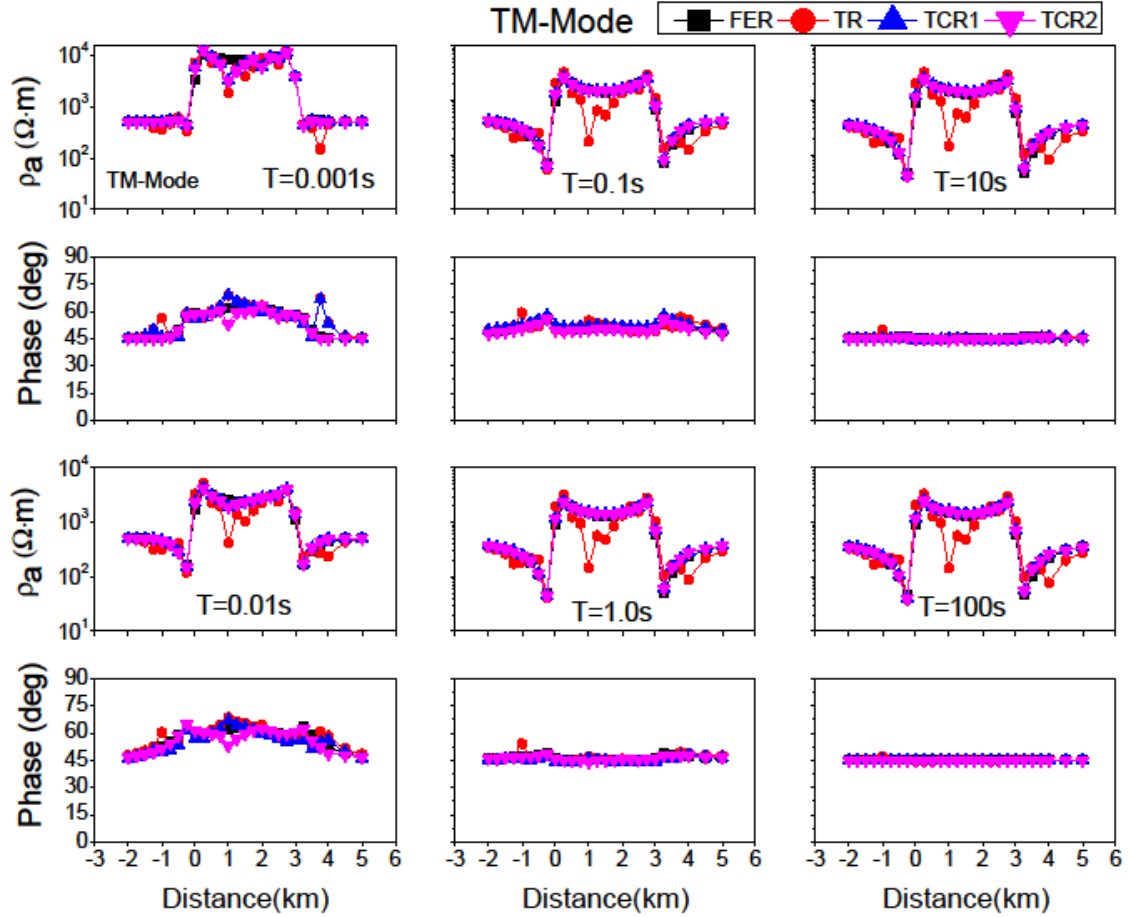
**Figure3:** Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) for the model in Figure 1 at six different periods (0.001 sec, 0.01 sec, 0.1 sec, 1sec, 10 sec and 100 sec).

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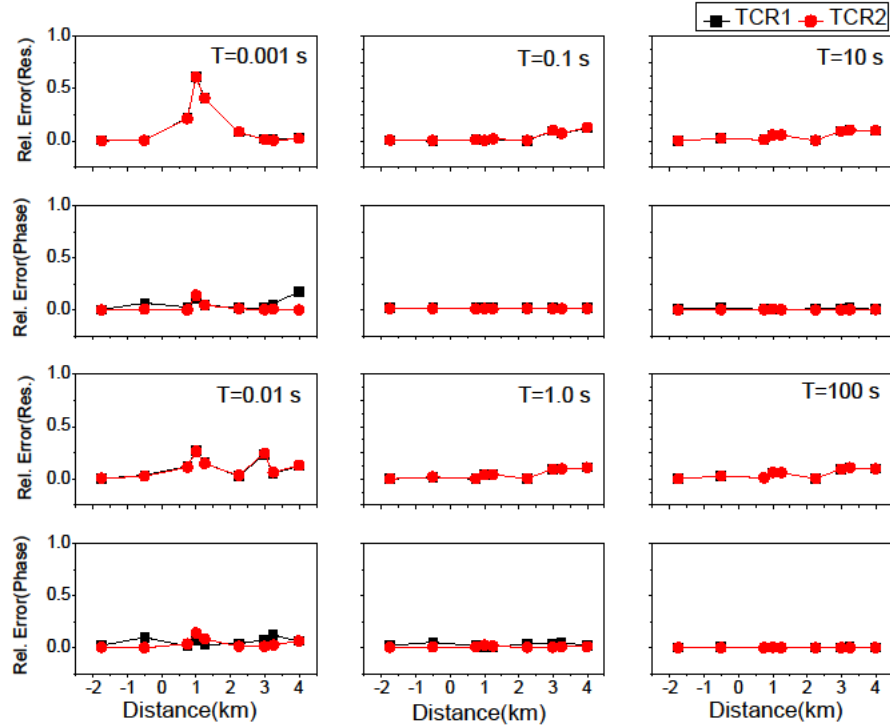


**Figure4:** Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth responses (apparent resistivity and phase) at six different periods with homogeneous half-space of 500 Ω·m resistivity.

## 4. MODELING OF ROORKEE TO GANGOTRI SECTION:

A theoretical analysis of the effect of topography on MT responses was also taken into account in the Himalayan topography model. A theoretical model of Roorkee-Gangotri Profile was generated to simulate the MT response. To compute the MT forward modeling responses over the rugged topographic surface in Roorkee to Gangotri section, the input model was prepared from a 2D inverted geoelectrical resistivity model (Tyagi, 2007). The topography model having an elevation of 2.75 km consists of a 180 km long profile from Roorkee to Gangotri drawn (Tyagi, 2007; Suman et al., 2023). In this model, two conductive blocks having resistivity 30 Ω·m and 10 Ω·m were embedded in a homogeneous half-space of 100 Ω·m resistivity. The first block of resistivity 30 Ω·m having width 80

173  km and thickness 6 km was embedded just near the earth's surface relief and the second block of width

174  40 km and thickness 25 km was embedded at 6 km depth from the surface. The MT responses were

175  computed by considering three models, (1) one with half-space of resistivity 100 Ω·m (Figure5a), (2)

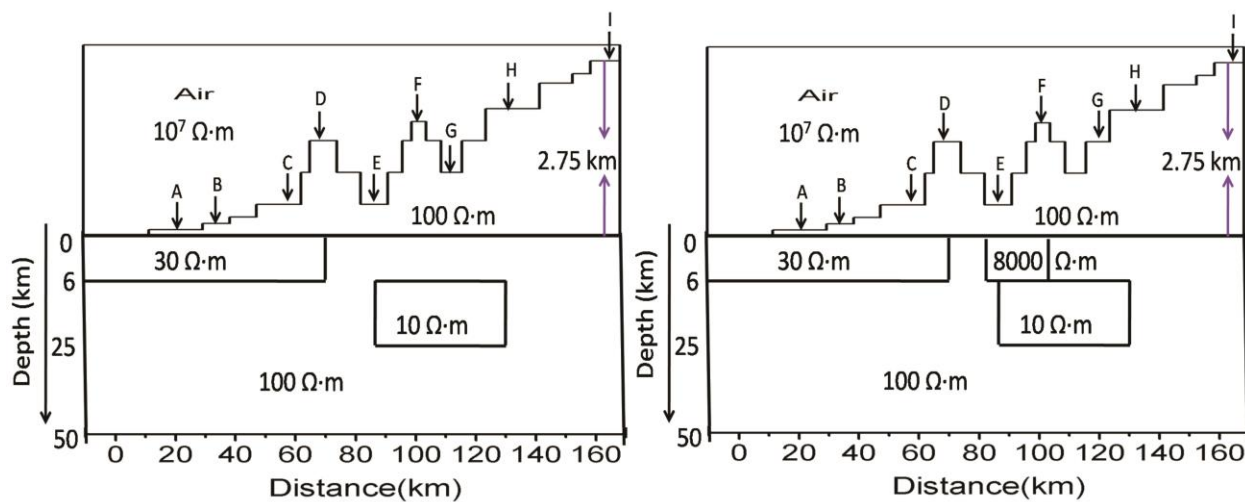
176  with half-space of resistivity 500 Ω·m, (3) with an additional resistive body of 8000 Ω·m embedded

177  from earth surface relief having thickness about 6 km with half-space of resistivity 100 Ω·m as shown

178  in Figure5b. The topography response (TR), flat earth response (FER) and two topography corrected

179  responses (TCR1 &TCR2) were analysed for nine sites (A, B, C, D, E, F, G, H& I) as shown in

180  Figure5 at six distinct periods (0.0013 sec, 0.0102 sec, 0.1063 sec, 1.1110 sec, 11.6078 sec, and

181  121.2813 sec).

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183  **Figure5:** (a) A Synthetic model of Garhwal Himalaya along Roorkee to Gangotri Profile in half-space

184  of resistivity 100 Ω·m(b) with a resistive block of resistivity 8000 Ω·m.

## 5.  RESULT AND DISCUSSION:

### 5.1.  Model with half-space of resistivity 100 Ω·m:

187  The topography response (TR) and flat earth response (FER) were computed for the topography

188  model with a conductive body of 30 Ω·m resistivity in a half-space of 100 Ω·m resistivity (Figure 5a)

189 and the topography corrections procedures were applied to the MT data. Figure6 shows the TM mode

190 of topography response (TR), flat earth response (FER) and two topography correction responses

191 (TCR1 & TCR2) at six different periods (0.0013 sec, 0.0102 sec, 0.1063 sec, 1.1110 sec, 11.6078 sec,

192 and 121.2813 sec). The topography effect depends upon the ramp/slope angle of the hill and is

193 significant when the slope angle is greater than 7.5$^\circ$ (Kumar et al., 2018). It is clear from Figure6 that

194 the TCR1 and TCR2 are almost similar to the topographic response, because the slope angle is less

195 than 1$^\circ$. The TCR1 &TCR2 were not similar to the flat earth response for the sites from A to D at

196 lower periods 0.0013 sec, 0.0102 sec, 0.1063 sec and 1.1110 sec, because of the exposure of the

197 conductive body having resistivity 30 $\Omega$·m to the surface (from A to D) and its galvanic effect. The

198 relative errors were also calculated between the FER with TCR1 and TCR2 and were high for the sites

199 A, B and C for lower periods (0.0013sec, 0.0102 sec and 0.1063 sec) due to the presence of the

200 conductive body underneath these sites and was very small for all other sites D, E, F, G, H and I at all

201 periods as shown in Figure7.

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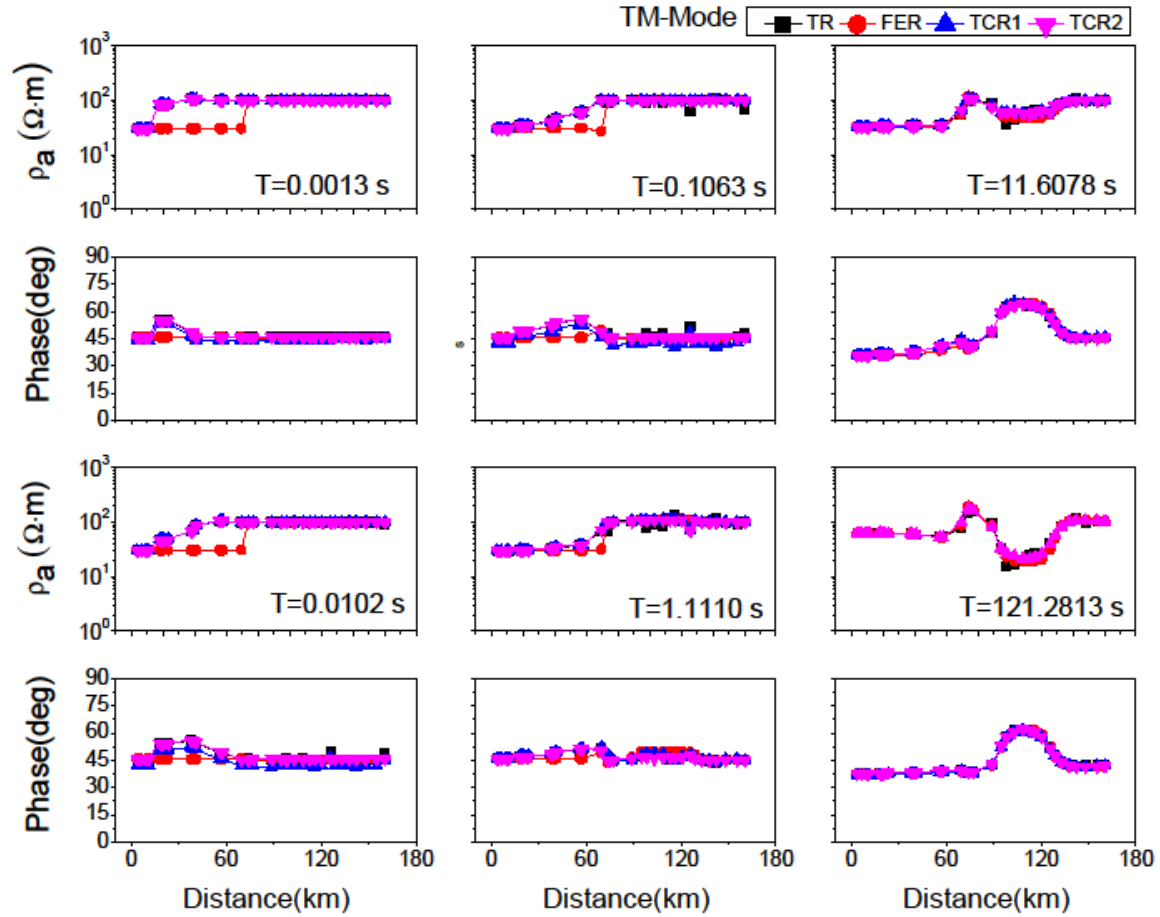
**Figure6:** Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) at six different periods for homogeneous half-space of resistivity100 Ω·m.

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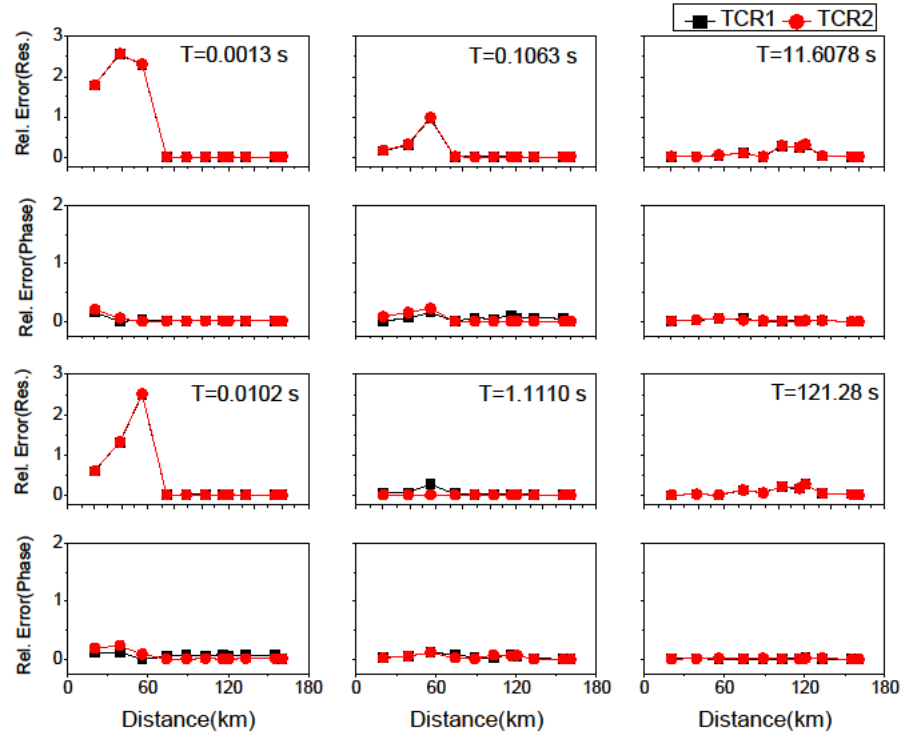
**Figure 7:** Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth response (apparent resistivity and phase) at six different periods with half-space of resistivity 100 Ω·m.

**5.2. Model with half-space of resistivity 500 Ω·m:**

Now consider the case in which model half-space resistivity was replaced with 500 Ω·min Figure 5a. The topography response (TR) and flat earth response (FER) were computed for the topography model with half-space of 500 Ω·m resistivity (Figure5a) and the topography correction procedures were applied to the MT data. Figure8 shows the TM component of topography response (TR), flat earth response (FER), and topography corrected responses (TCR1 & TCR 2) at six different periods. The results were almost similar to the response of the model with half-space of resistivity 100 Ω·m. The relative errors were also calculated in this case also between the FER with TCR1 and TCR2 and the results were similar to the model with half-space of 100 Ω·m at all these periods (0.0013 sec, 0.0102 sec, 0.1063 sec, 1.1110 sec, 11.6078 sec, and 121.2813 sec) as shown in Figure 9.

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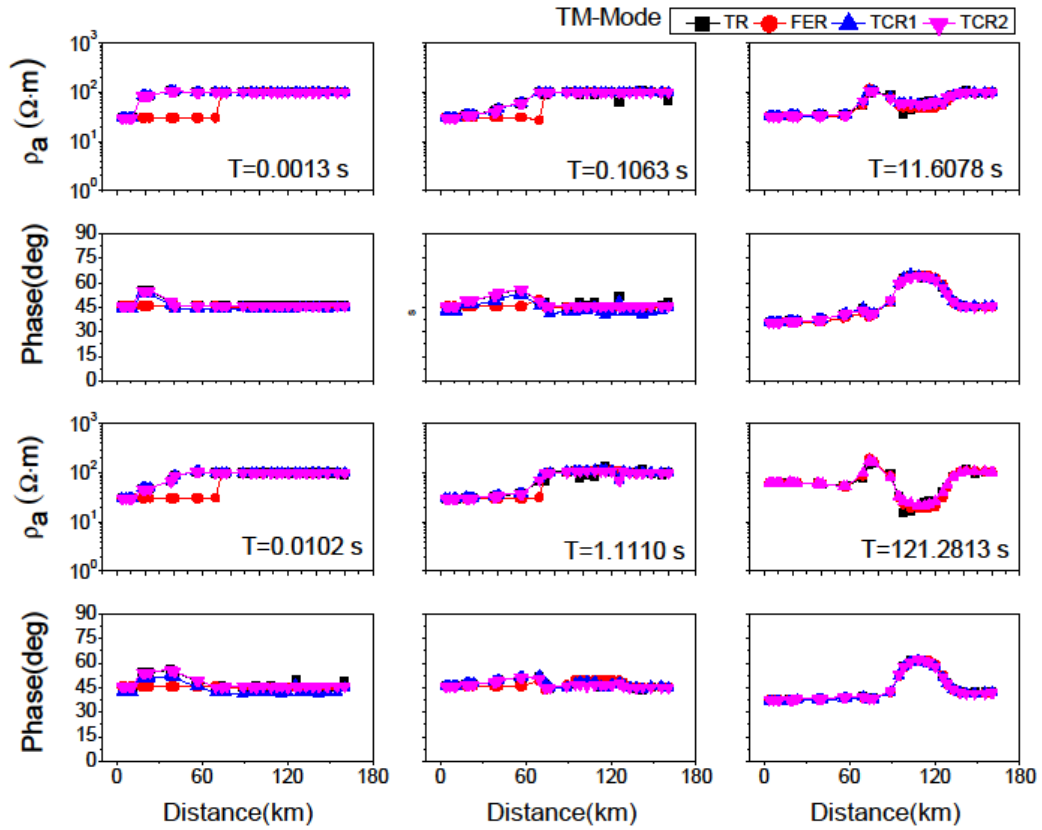
**Figure8:** Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) at six different periods for half-space of resistivity 500 Ω·m.

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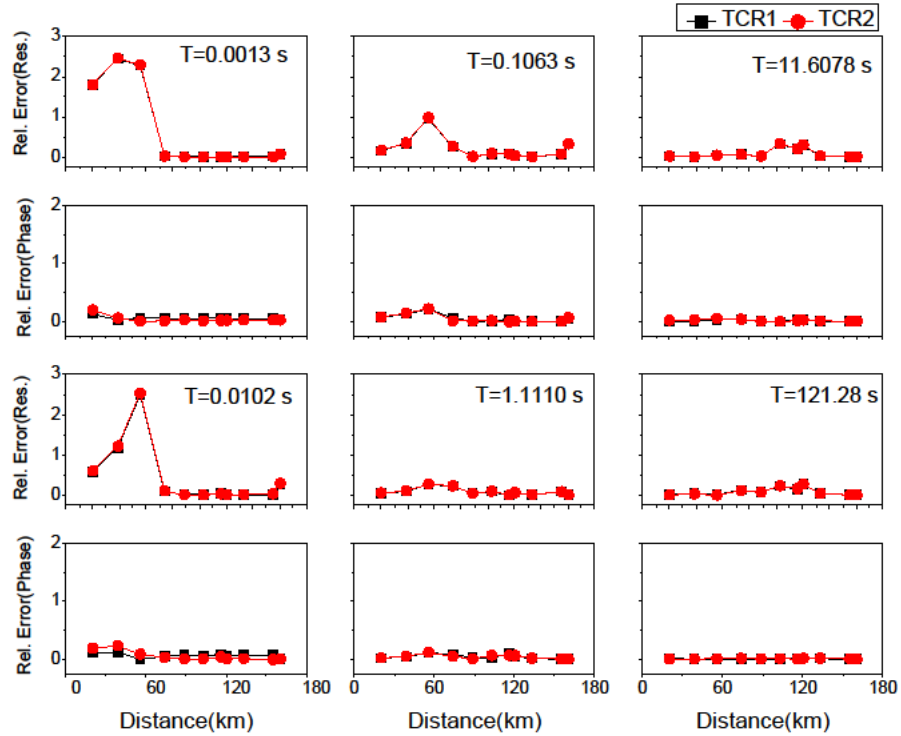


**Figure9:** Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth response (apparent resistivity and phase) at six different periods with half-space of resistivity 500 Ω·m.

**5.3. Model with a resistive block of resistivity 8000 Ω·m in half-space of 100 Ω·m:**

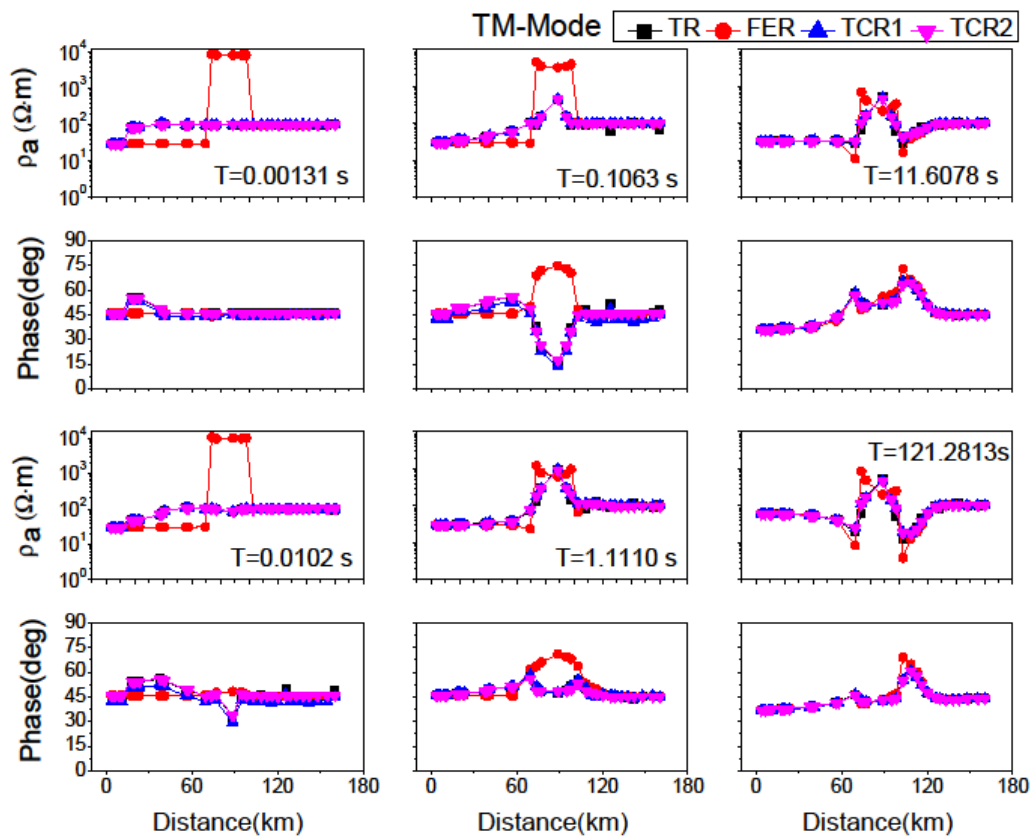
The topography response (TR) and flat earth response (FER) were also computed for the topography model with a resistive block of resistivity 8000 Ω·m in half-space of 100 Ω·m resistivity (Figure 5b) and the topography corrections were applied to the MT data. Figure10 shows the TM component of topography response (TR), flat earth response (FER) and two topography correction responses (TCR1 & TCR2) at six different periods. The TCR1 & TCR2 were not similar to the flat earth model for the sites from A to F, because of the exposure of the conductive body having resistivity 30 Ω·m to the surface (from A to D) and its galvanic effect and the presence of 8000 Ω·m resistive body (from D to

236  F). The relative errors were also calculated between the FER with TCR1 and TCR2 and were high for

237  the sites A, B and C for lower periods (0.0013 sec, 0.0102 sec and 0.1063 sec) due to the presence of

238  the conductive body underneath these sites and for higher periods (1.1110 sec, 11.6078 sec and

239  121.2813 sec) the relative error was again high due the presence of the 8000 Ω·m resistive body from

240  D to F as shown in Figure 11.

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242  **Figure10:** Comparison of TM components of flat earth response (FER), topographic response (TR),

243  and two correction procedures (TCR1 and TCR2) at six different periods for half-space of resistivity

244  100 Ω·m.

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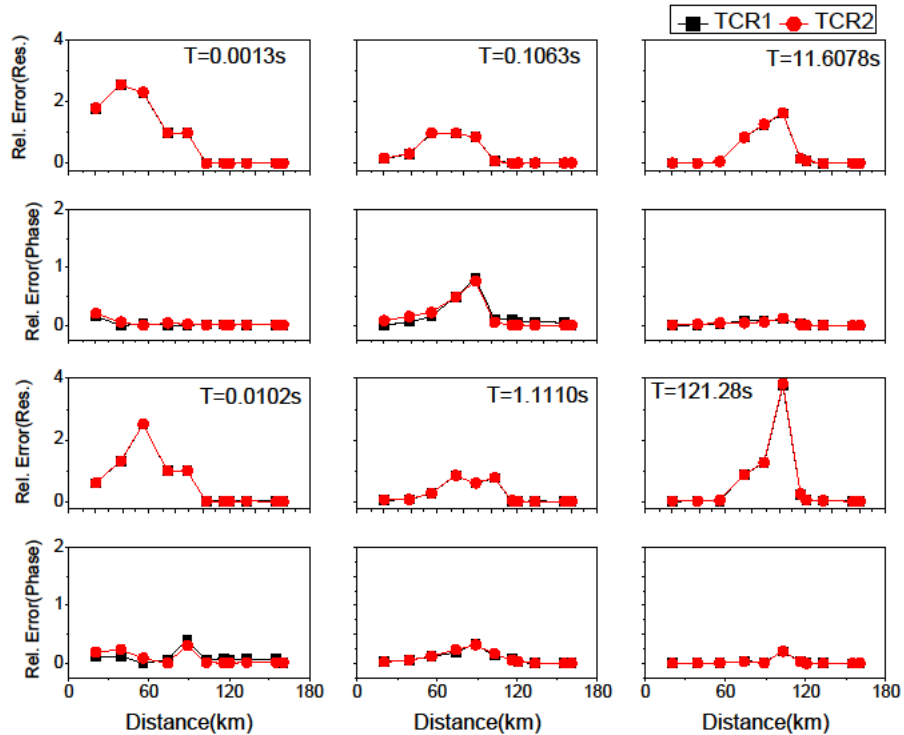
**Figure11:** Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat

earth response (apparent resistivity and phase) at six different periods with half-space of resistivity

100 Ω·m.

## 6. CONCLUSIONS:

The study shows the effect of topography in the MT data along a synthetic model of Roorkee-

Gangotri profile.The two correction procedures were used to remove the topography distotion from

MT data. The similar FER, TCR1 and TCR2 in Figure. 3 shows that the both correction procedures

are capable to remove the topography effect, this shows the accuracyof the two correction procedures.

The similar TR, TCR1and TCR2 responses (Figure6, 8 and 10) concluded that there is no need for

topography correction along Roorkee-Gangotri Profile, because the slope angle is less than one

degree. The relative error between the FER and TCR1 and TCR2 also showed the accuracy of the two

257 correction procedures (TCR1 & TCR2) in this study. The presence of near surface
258 hetrogeneity/surface exposure of conductive/resistive body also distort the MT responses as in this
259 model (the FER not similar to TR, TCR1 and TCR2).

## ACKNOWLEDGEMENT

261 S. Saini thank Head of Department, Department of Physics, M. M. Engineering College, Maharishi
262 Markandeshwar (Deemed to be) University for continuous guidance and support throughout this
263 research.

## AUTHOR CONTRIBUTION:

265 Dr. Deepak Kumar Tyagi and Ms. Suman Saini designed the experiments, developed the model
266 and performed the simulations. Dr Rajeev Sehrawat, Dr. Sushil Kumar prepared the manuscript
267 with contributions from all the co-authors.

## COMPETING INTERESTS

269 The authors declare that they have no conflict of interest.

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