Modeling of terrain effect in magnetotelluric data from Garhwal Himalaya Region

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ABSTRACT

Magnetotelluric methods (MT) are passive geophysical techniques based on time variations of the geoelectric and geomagnetic field in order to measure the electrical resistivity of surface layer. It is most effective geophysical techniques to study the deep structure of the Earth's crust, particularly in steep terrain like the Garhwal Himalaya region. The MT responses are distorted as a result of the undulated/rugged terrain. Such responses, if not corrected, can lead to a misinterpretation of MT data for the geoelectrical structures. In this study, two different correction procedures were used to compute the topography distortion for the synthetic model of Garhwal Himalaya region from Roorkee to Gangotri section. A finite difference algorithm was used to compute MT responses (apparent resistivity and phase) for the irregular terrain. The accuracy of the terrain correction procedures was checked on results published in the literature on different topography models at various periods. The relative errors between two terrain correction procedures were calculated with respect to flat earth and were very less or almost zero for most of the sites along the Roorkee to Gangotri profile except at the foothill where the error was high at lower periods. The similar topography response, terrain corrected

responses TCR1 and TCR2 responses concluded that there is no need for topography correction along Roorkee-Gangotri Profile because the slope angle is less than one degree.

Keywords: Magnetotelluric, Topography correction procedures, Himalaya region

1. INTRODUCTION

The magnetotelluric (MT) method was first explored by Tikhonov (1950) and Cagniard (1953) and was used to analyse the time-varying measured components of earth's natural time-varying electric and magnetic fields to determine the shallow layers of the Earth. MT technique has been successfully used to explore a variety of earth resources, including oil, gas, mineral, and geothermal energy (Zhang et al., 2014; Patro et al., 2017; Mohan et al., 2017). The MT method is effective for analysing deep crystal structures in challenging undulating terrains, such as the Himalayan region as compared to the seismic method (Tyagi , 2007; Israil et al., 2008, 2016; Pavan Kumar et al., 2014; Patro and Harinarayana, 2009; Kumar et al., 2018, 2022; Xiong-Bin, 2020; Dharmendra Kumar et al., 2021; Konda et al., 2023). Topography affects both the electric field and magnetic field components due to undulating topographical features like hills and valleys, which distort the current lines (Wannamaker et al., 1986; Michel Choutraus et al., 1988; Changhong et al., 2018; Kumar et al., 2018, 2022). Therefore, the MT response functions impedance and apparent resistivity get distorted when the MT sites are on or near the top of the hill or close to the valley.

Analytical and numerical techniques have been used to measure the topography distortion effect from MT data. Analytical techniques based on conformal mapping were used by Thayer (1975), Harinarayana and Sarma (1982). The 2D numerical techniques have been used for different type terrain geometries to remove topography effects from the data. The analogue, analytic, and numerical solution methods were used to study the analogue model (Wescott and Hessler, 1962; Faradzhev et al., 1972).Various two-dimensional (2D) numerical techniques have been used for the numerical treatment of the topographic effects like networking analogy (Ku et al., 1973; NgCo, 1980) and Rayleigh scattering numerical modeling techniques (Reddig and Jiracek, 1984; Jiracek et al., 1989), finite element method (Wannamaker Stodt and Rijo, 1986; Frankle et al., 2007) and finite difference method (Josef Pek and Tomas Verner, 1996; Yutaka Sasaki, 2003 and Tyagi et al., 2007). The distortions in MT data due to topography and near-surface inhomogeneities have been observed by many researchers (Michel Choutraus et al., 1988;Jiracek, 1990; Vozoff, 1991). The distortion tensor stripping-off technique has been used to reduce the topographic effect and to remove the distortion due to the near-surface heterogeneity (Larsen, 1971). The analogue, analytic, and numerical solution methods were used to study the analogue model (Wescott and Hessler, 1962; Faradzhev et al., 1972).Various two-dimensional (2D) numerical techniques have been used for the numerical treatment of the topographic effects like networking analogy (Ku et al., 1973; NgCo, 1980) and Rayleigh scattering numerical modeling techniques (Jiracek Redding and Kojima, 1989) and finite element method (Wannamaker Stodt and Rijo, 1986; Frankle et al., 2007). In 2D, the topography effect is galvanic in Transverse Magnetic (TM) mode and inductive in Transverse Electric (TE) mode, hence more distortion in TM mode than TE mode (Gurer and Ilikisik, 1997; Kumar et al., 2014; Kumar et al., 2018, 22).

In this study, modified 2D forward and inversion modeling code EM2INV (Rastogi, 1997) based on the finite difference method were used to compute MT forward modeling responses over flat earth and topographic surface. Two different terrain correction procedures have been used in this study: first correction procedure was adopted from Chouteau and Bouchard (1988) and the second was adopted from Nam et al., (2008) to compute the topography distortion for the synthetic model of

GarhwalHimalayan region (Roorkee-Gangotri section). The results of both terrain correction procedures have been compared with the model used by Chouteau and Bouchard (1988).

2. METHODOLOGY

The topography correction to the MT data has been applied by two different techniques. The first technique was introduced by Chouteau and Bouchard (1988) to estimate the distortion tensor and correction of MT data before inversion of MT data. In the second approach, the distortion tensor stripping-off technique was used to remove the distortion from the MT data (Larsen, 1977 and Nam et al., 2008). Two correction procedures, first adopted by Chouteau and Bouchard (1988) and second by Nam et al., (2008), were used to correct the MT data.

2.1 Terrain correction procedure 1 (TCP1):-

The computational algorithm for 2D forward modeling has been used to account for irregular terrain. The distortion tensor for the topographic effect was calculated using the technique adopted by Chouteau and Bouchard (1988). Based on the assumption that the topography distorted subsurface field can be approximated by multiplying the distortion tensor by the subsurface field for a flat earth given by:

$$\widetilde{E_D} = D\widetilde{E_N} \qquad (1)$$

where $\widetilde{E_D}$ and $\widetilde{E_N}$ are the distorted and normal electric field matrices with elements $E(f,r)_D$ and $E(f,r)_N$ respectively. $\widetilde{D}$ is the distortion tensor with elements $D(f,r)$, where f is frequency and r is the measuring site position. In case of 2D problem in TM mode and x-axis is the direction of strike, equation (1) can be written as

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

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

$$Z_D(f,x) = D(f,x)Z_N(f,x) \quad (3)$$

where $Z_N(f,x)$ and $Z_D(f,x)$ are respectively the normal (flat earth) impedance and distortion impedance. The complex coefficients $D(f,x)$ are distortion coefficients that should just reflect topography effect. The distortion coefficients are calculated by normalizing the impedances $Z_t(f,x)$ computed over topographic model above a homogeneous medium with the half-space impedance. Thus, the corrected impedance over flat earth can be calculated by taking the following ratio of the observed impedances, $Z_D(f,x)$, over irregular topography to the distortion coefficients $D(f,x)$:

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

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

2.2 Terrain correction procedure 2 (TCP2) :-

In this correction procedure, the MT data was corrected using the technique adopted by Nam et al., (2008). Larsen (1977) introduced the distortion tensor stripping-off technique, in which the undistorted impedance tensor can be calculated using a linear relationship between the distorted and undistorted impedance tensor, and topography distorted MT data can be corrected by computing the distortion tensor. The undistorted impedance tensor is linearly related to the distorted impedance tensor as:

$$Z^D = D^Z . Z^U \quad (5)$$

where Z^D is the distortion impedance tensor, D^Z is distortion tensor and Z^U is the undistorted impedance tensor respectively. The distortion tensor can be calculated from the relation between the impedance tensor for a homogeneous medium with topography earth surface (Z^t), and that with the flat earth surface (Z^h) as

$$Z^t = D^Z . Z^h \tag{6}$$

In case of 2D, $Z^h_{xx} = Z^h_{yy} = (0, 0)$ and $Z^h_{xy} \neq -Z^h_{yx}$, the inhomogeneous earth distortion tensor, equations (5) and (6) can be rewritten in matrix form as

$$\begin{bmatrix} 0 & Z^D_{xy} \\ Z^D_{yx} & 0 \end{bmatrix} = \begin{bmatrix} 0 & D^Z_{xy} \\ D^Z_{yx} & 0 \end{bmatrix} \begin{bmatrix} 0 & Z^U_{xy} \\ Z^U_{yx} & 0 \end{bmatrix} \tag{7}$$

and

$$\begin{bmatrix} 0 & Z^t_{xy} \\ Z^t_{yx} & 0 \end{bmatrix} = \begin{bmatrix} 0 & D^Z_{xy} \\ D^Z_{yx} & 0 \end{bmatrix} \begin{bmatrix} 0 & Z^h_{xy} \\ Z^h_{yx} & 0 \end{bmatrix} \tag{8}$$

So

$$\begin{bmatrix} 0 & D^Z_{xy} \\ D^Z_{yx} & 0 \end{bmatrix} = \begin{bmatrix} 0 & Z^t_{xy} \\ Z^t_{yx} & 0 \end{bmatrix} \begin{bmatrix} 0 & Z^h_{xy} \\ Z^h_{yx} & 0 \end{bmatrix}^{-1} \tag{9}$$

$$\begin{bmatrix} 0 & D^Z_{xy} \\ D^Z_{yx} & 0 \end{bmatrix} = \begin{bmatrix} (Z^t_{xy})/(Z^h_{xy}) & 0 \\ 0 & (-Z^t_{yx})/(Z^h_{yx}) \end{bmatrix} \tag{10}$$

Substituting equation (10) in equation (7)

$$\begin{bmatrix} 0 & Z^D_{xy} \\ Z^D_{yx} & 0 \end{bmatrix} = \begin{bmatrix} (Z^t_{xy})/(Z^h_{xy}) & 0 \\ 0 & (-Z^t_{yx})/(Z^h_{yx}) \end{bmatrix} \begin{bmatrix} 0 & Z^U_{xy} \\ Z^U_{yx} & 0 \end{bmatrix} \tag{11}$$

The undistorted or corrected impedance tensor component can be obtained as

So

$$Z^U_{xy} = (Z^h_{xy} Z^D_{xy})/(Z^t_{xy}) \tag{12}$$

$$Z^U_{yx} = (Z^h_{yx} Z^D_{yx})/(Z^t_{yx}) \tag{13}$$

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). 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 Figure 2. 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).

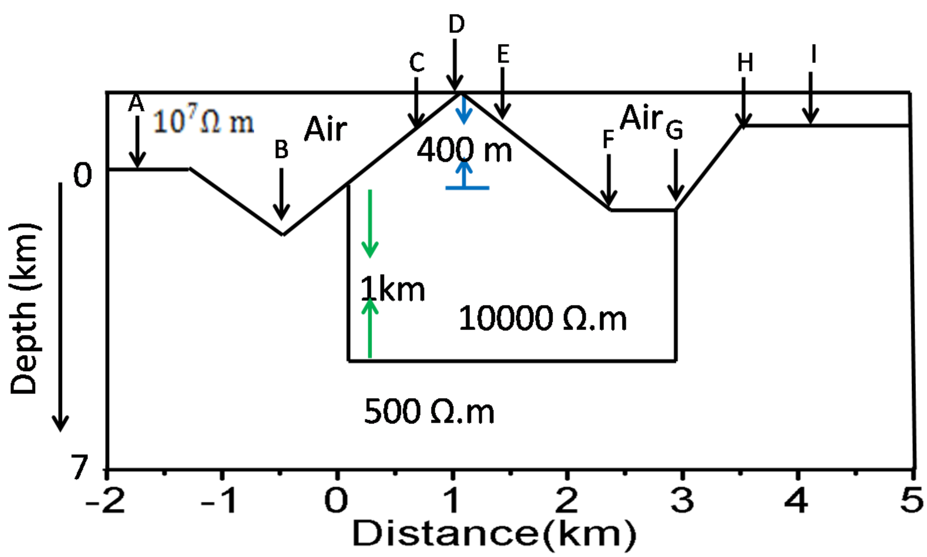

Figure1: Topographic model of 500 Ω.m half-space with a resistive body of 10 kΩ.m was embedded from the surface relief (Chouteau and Bouchard, 1988).

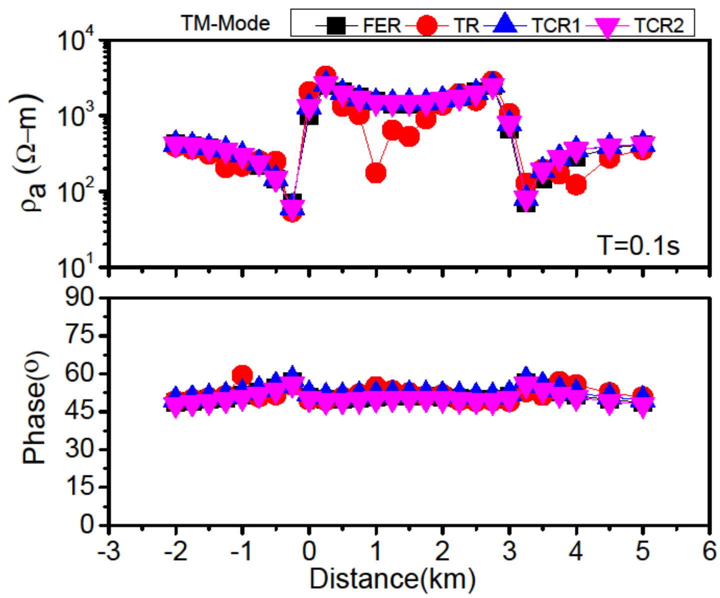

Figure 2: Comparison of TM component of flat earth response (FER), topographic response (TR) and two terrain correction responses (TCR1 and TCR2) at 0.1 sec.

Figure 3 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 Figure 4. This shows the accuracy of the correction procedures.

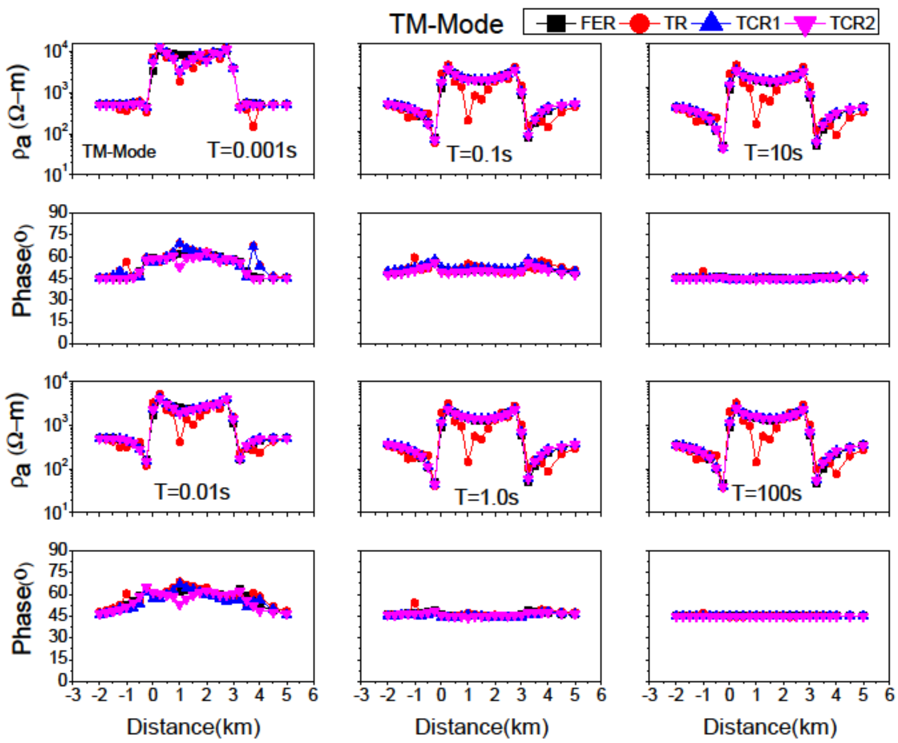

Figure 3: Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) for the model in Figure 1 at six different periods (0.001 sec, 0.01 sec, 0.1 sec, 1sec, 10 sec and 100 sec).

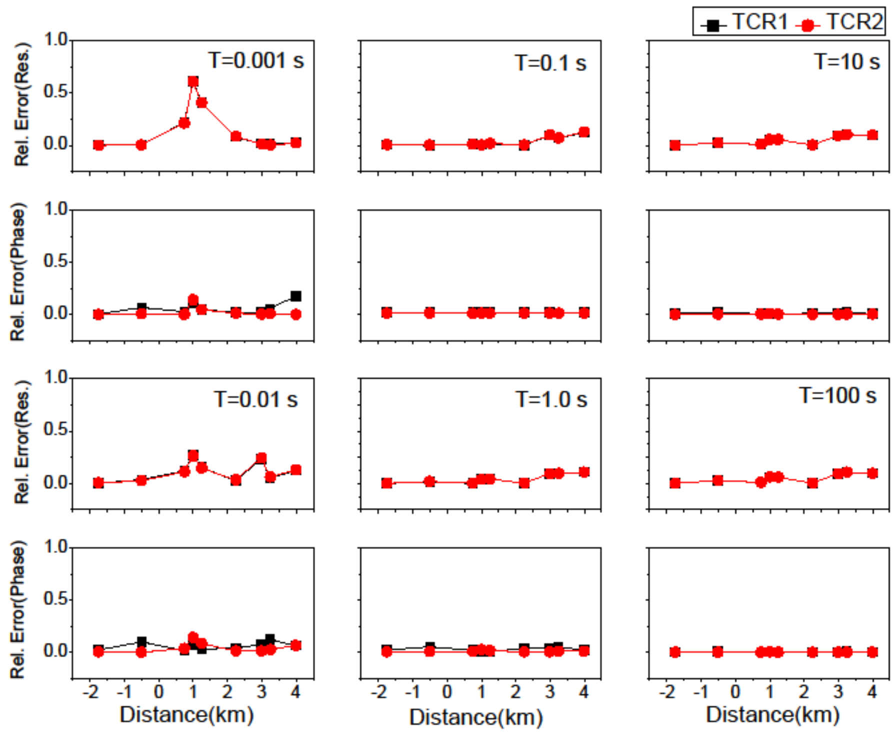

Figure 4: Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth responses (apparent resistivity and phase) at six different periods with homogeneous half-space of 500 Ω.m resistivity.

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 km and thickness 6 km was embedded just near the earth's surface relief and the second block of width 40 km and thickness 25 km was embedded at 6 km depth from the surface. The MT responses were computed by considering three models, (1) one with half-space of resistivity 100 Ω.m (Figure5a), (2) with half-space of resistivity 500 Ω.m, (3) with an additional resistive body of 8000 Ω.m embedded from earth surface relief having thickness about 6 km with half-space of resistivity 100 Ω.m as shown in Figure 5b. The topography response (TR), flat earth response (FER) and two topography corrected responses (TCR1 &TCR2) were analysed for nine sites (A, B, C, D, E, F, G, H& I) as shown in Figure 5 at six distinct periods (0.0013 sec, 0.0102 sec, 0.1063 sec, 1.1110 sec, 11.6078 sec, and 121.2813 sec).

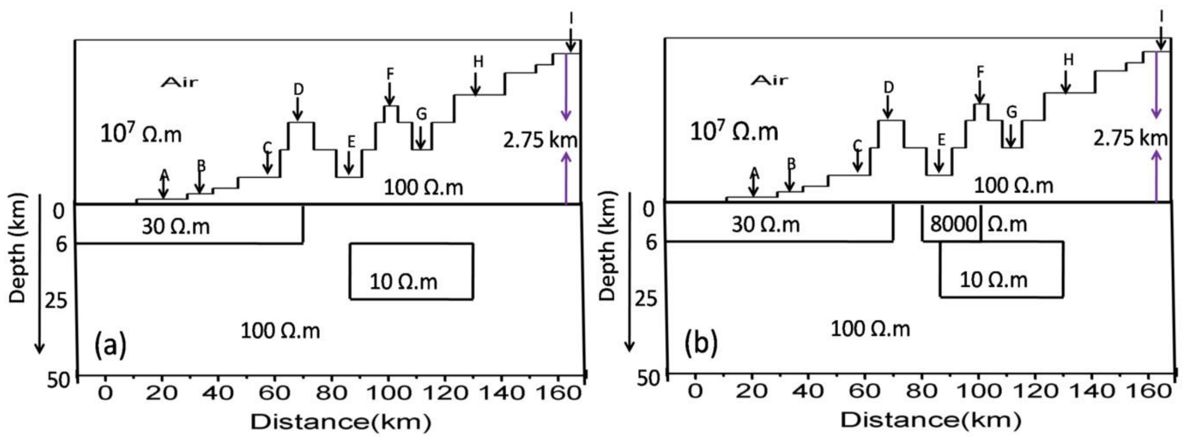

Figure 5: (a) A Synthetic model of Garhwal Himalaya along Roorkee to Gangotri Profile in half-space of resistivity 100 Ω.m (b) with a resistive block of resistivity 8000 Ω.m.

5. RESULT AND DISCUSSION:

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

The topography response (TR) and flat earth response (FER) were computed for the topography model with a conductive body of 30 Ω.m resistivity in a half-space of 100 Ω.m resistivity (Figure 5a) and the topography corrections procedures were applied to the MT data. Figure 6 shows the TM mode of topography response (TR), flat earth response (FER) and two topography correction responses (TCR1 & TCR2) at six different periods (0.0013 sec, 0.0102 sec, 0.1063 sec, 1.1110 sec, 11.6078 sec, and 121.2813 sec). The topography effect depends upon the ramp/slope angle of the hill and is significant when the slope angle is greater than 7.5^{o} (Kumar et al., 2018). It is clear from Figure 6 that the TCR1 and TCR2 are almost similar to the topographic response, because the slope angle is less than 1^{o}. The TCR1 &TCR2 were not similar to the flat earth response for the sites from A to D at lower periods 0.0013 sec, 0.0102 sec, 0.1063 sec and 1.1110 sec, because of the exposure of the conductive body having resistivity 30 Ω.m to the surface (from A to D) and its galvanic effect. The relative errors were also calculated between the FER with TCR1 and TCR2 and were high for the sites A, B and C for lower periods (0.0013sec, 0.0102 sec and 0.1063 sec) due to the presence of the conductive body underneath these sites and was very small for all other sites D, E, F, G, H and I at all periods as shown in Figure 7.

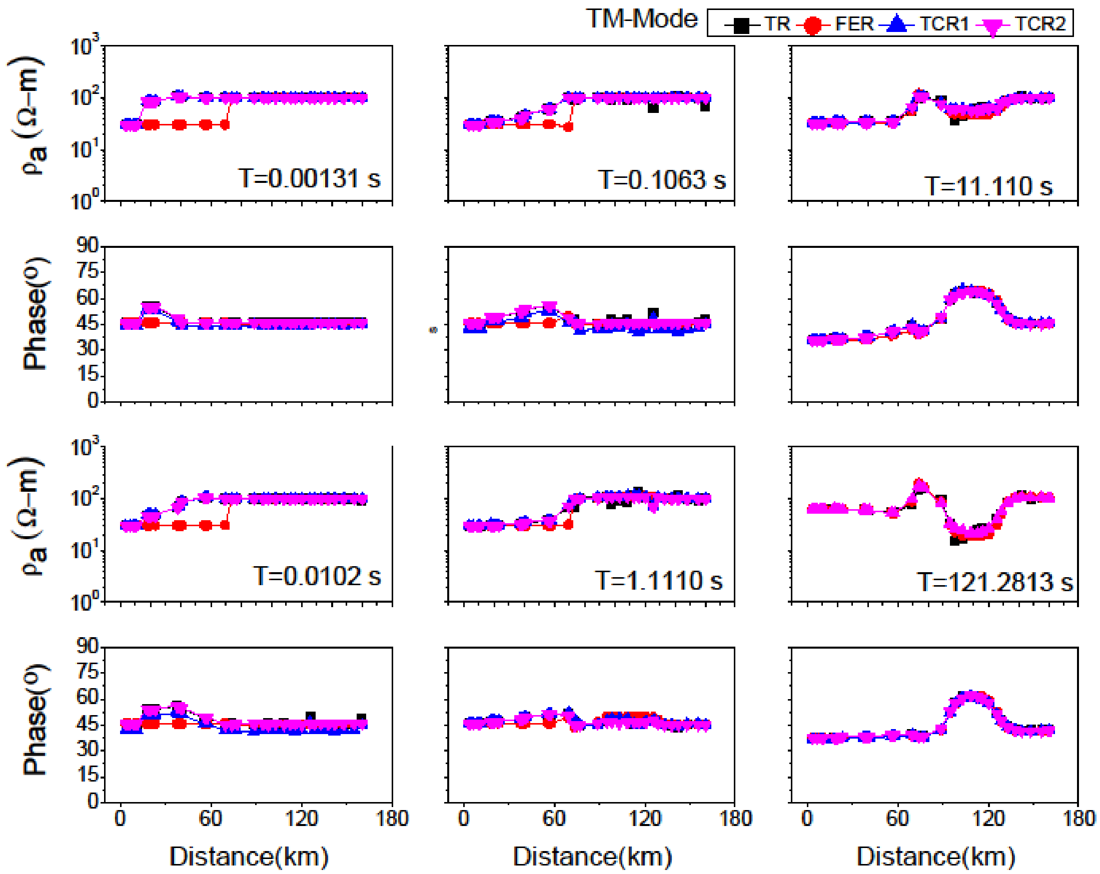

Figure 6: Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) at six different periods for homogeneous half-space of resistivity100 Ω.m.

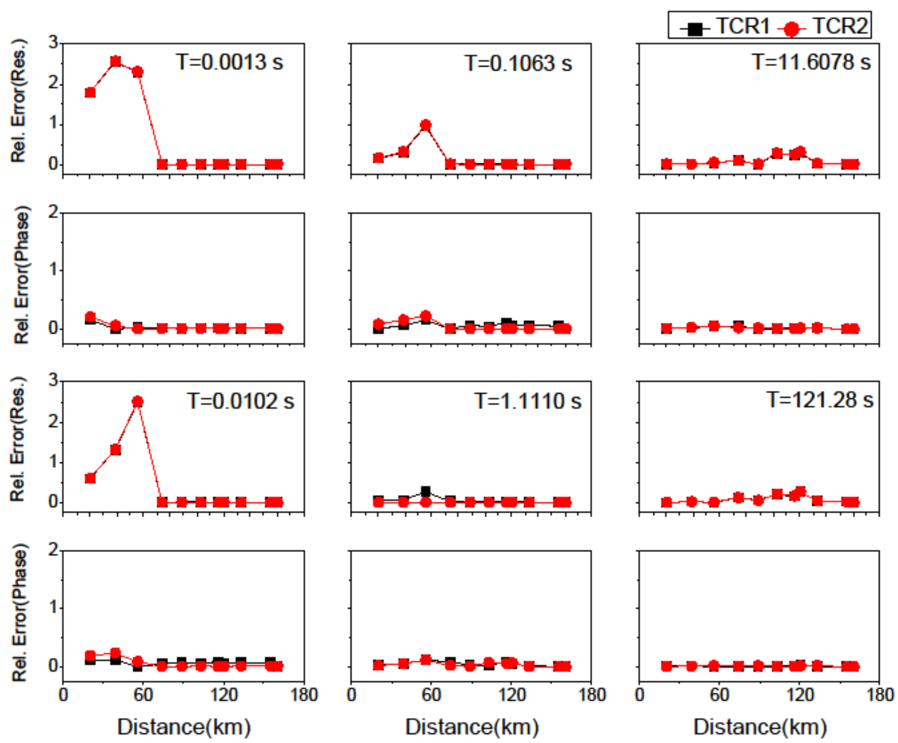

Figure 7: Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth response (apparent resistivity and phase) at six different periods with half-space of resistivity 100 Ω.m.

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.m in 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 (Figure 5a) and the topography correction procedures were applied to the MT data. Figure 8 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.

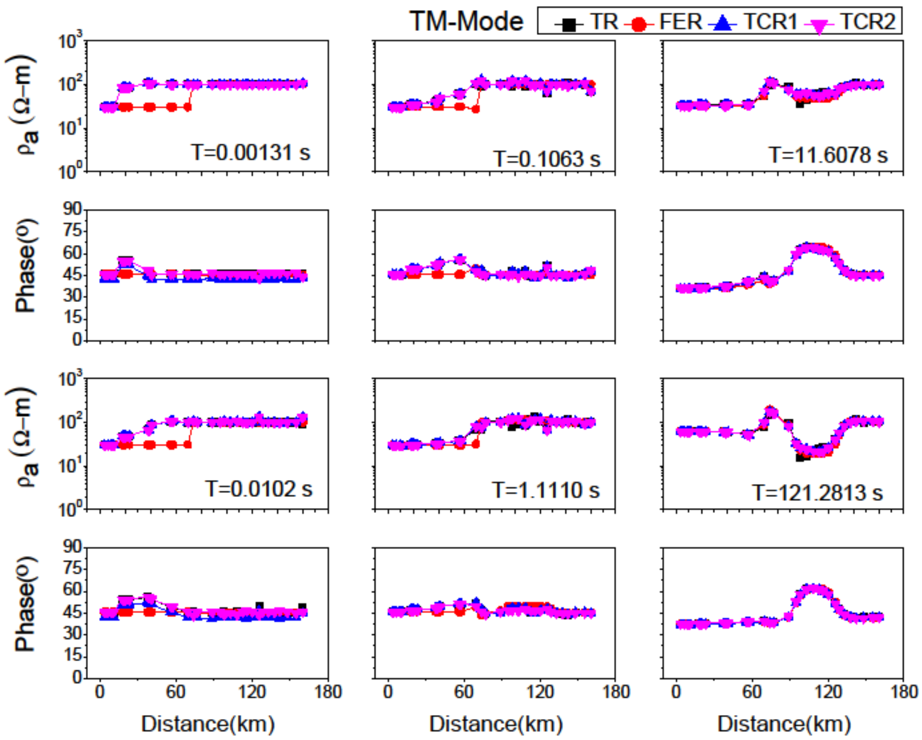

Figure 8: Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) at six different periods for half-space of resistivity 500 Ω.m.

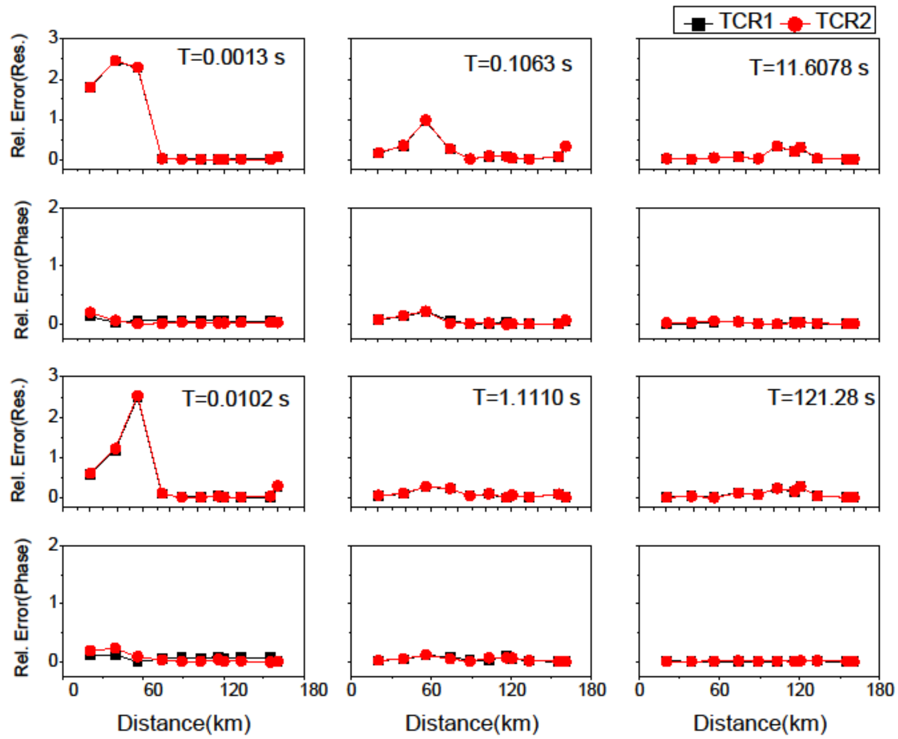

Figure 9: Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth response (apparent resistivity and phase) at six different periods with half-space of resistivity 500 Ω.m.

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

F). The relative errors were also calculated between the FER with TCR1 and TCR2 and were high for the sites A, B and C for lower periods (0.0013 sec, 0.0102 sec and 0.1063 sec) due to the presence of the conductive body underneath these sites and for higher periods (1.1110 sec, 11.6078 sec and 121.2813 sec) the relative error was again high due the presence of the 8000 Ω.m resistive body from D to F as shown in Figure 11.

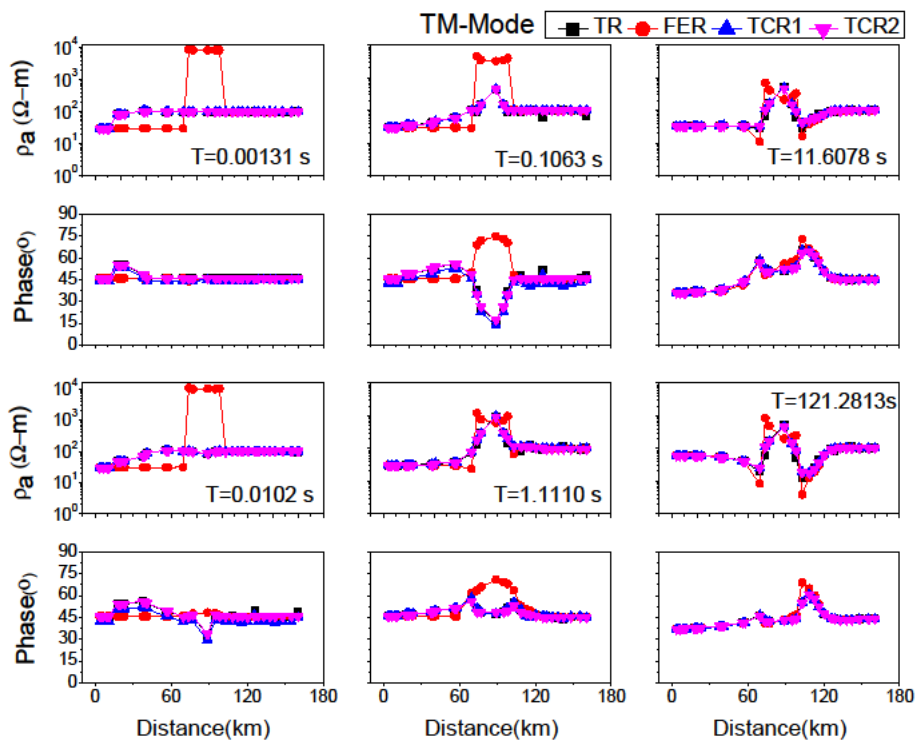

Figure10: Comparison of TM components of flat earth response (FER), topographic response (TR), and two correction procedures (TCR1 and TCR2) at six different periods for half-space of resistivity 100 Ω.m.

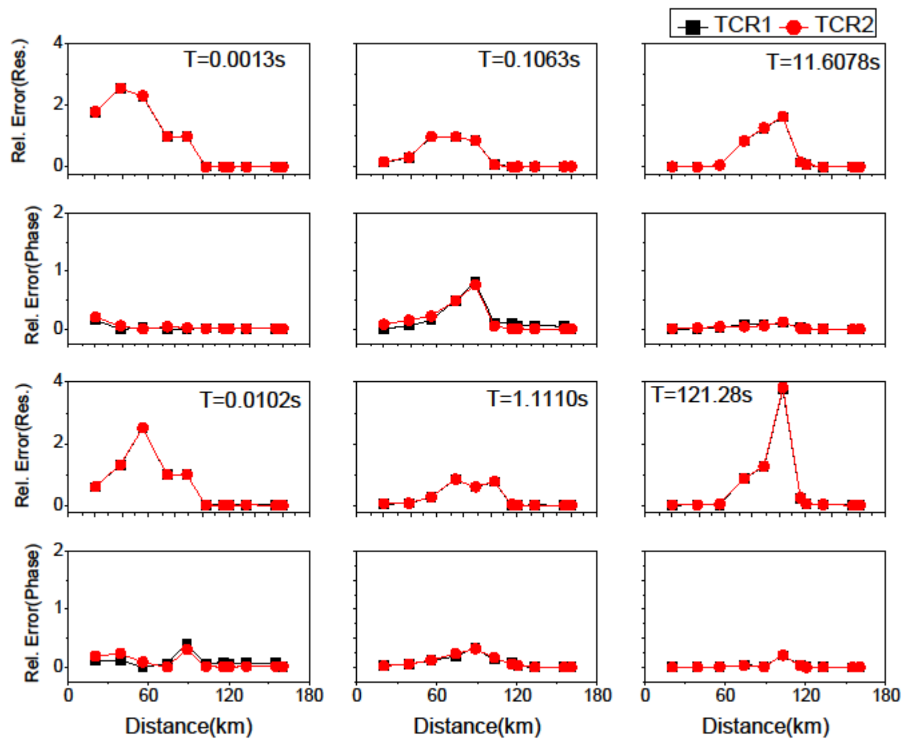

Figure 11: Relative error between terrains corrected responses (TCR1 and TCR2) with respect to flat earth response (apparent resistivity and phase) at six different periods with half-space of resistivity 100 Ω.m.

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

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AUTHOR CONTRIBUTION:

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

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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