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Topography distortion effect on Magnetotelluric (MT) profiling of Sub-Himalayan region using two-dimensional modeling

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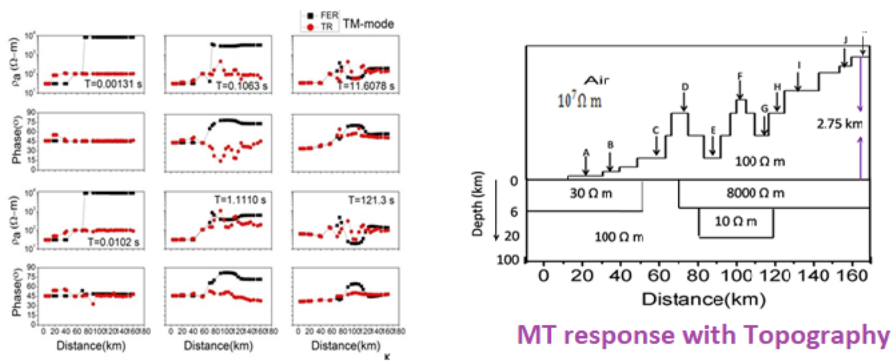
ABSTRACT



In order to correctly understand the earth's subsurface resistivity structure, it is vital to take into account and analyze topography influenced magnetotelluric (MT) data. To compute MT responses (impedance, apparent resistivity, and phase) over undulating topography, a Finite Difference Method (FDM) based algorithm is modified. The modified algorithm was tested using models that have already been published in the literature, and MT responses were computed for both TE and TM mode at various periods. While there are certain discrepancies resulting from discretization approaches, the computed and reported results are generally in worthy agreement. It has been noted that the electric current flowing across and along the strike direction causes the TM-mode responses to be more distorted than TE-mode responses. A synthetic investigation of topography's impact on MT data also takes into account 2D inverted geoelectric model from the Garhwal Himalaya region that is based on field data. MT responses are computed over a range of periods between 0.001 - 121 seconds on topography and flat earth surface. Along the Roorkee-Gangotri profile at 32 sites, the distortion effect in MT data caused by the complex Himalayan topography is examined at six different time periods. It has been shown that distortion effects in MT data are most pronounced at low periods($< 1\ sec.$). The sites that are at or near hilltops and in valleys have more distorted MT responses, as evidenced by the relative errors analysis between topography and flat earth responses.

Keywords: Magnetotelluric, Numerical modeling, Topography Distortion effect, Himalaya region

INTRODUCTION

Magnetotelluric (MT) is a passive electromagnetic technique to estimate the subsurface resistivity of the Earth's interior by using the simultaneous measured orthogonal components of natural time varying electric and magnetic fields on the surface of earth.[1] The primary MT field is assumed to be a plane EM wave that propagates vertically downward based on the MT theory. Now-a-days, the MT approach has been successfully employed for a variety of applications that relate to subsurface resistivity structure at various depth scales.[2] Examples include the exploration of minerals, geothermal, oil and gas resources, and other types of Earth resources.[3] In comparison to seismic method, the MT method is efficient for deep crystal structure investigation in complex undulating terrains like the Himalayan region.[4] The undulating topography features, hill and valley types modify the pattern of current flow.[5,6] Thus topography affects both the magnetic field and electric field components at different degrees of inclination. Hence MT response function (impedance, apparent resistivity, and phase) becomes distorted when the observation sites are located on or near the top and in the vicinity of undulating topography. By assuming the homogenous earth's subsurface resistivity, the topographic distortion is calculated analytically.[7] Jiracek[8] has provided classification and explanation of the EM distortions due to topography and near-surface inhomogeneities. Numerous studies have looked into the influence of the terrain on MT data using numerical, analytical, and analogous methodologies.

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The analogous method has been studied by Wescott and Hassler[9] and Faradzhevetal.[10] Based on unformed techniques; analytical solutions have been carried out by many researchers.[11] Numerical methods which are applying to several terrain geometrics can also be adopted for the analysis of topographic effects using the MT data. Numerous methods have been documented in the literature for the topography impacts numerical solutions.[12]

There are distinct numerical methods thatare generally adopted in magnetotelluric modeling, e.g. Hybrid method,[13] the finite element method (FEM)[14] the FDM method,[15] and the integral equation method.[16] Because of the consumption of reduced computational time and memory storage and drawback of the structured rectangular mesh, the FDM seems to be accurate for simple modeling. Because of the higher flexibility of mesh, FEM seems to be more precise for complex modeling, especially bathymetry and topography.[17,18] The longer time consumption and greater consumption of memory storage are the disadvantages of FEM. The FDM is used in the present research work to study the complex topography effect from the MT data.

BASIC THEORY OF MT METHOD

By considering the linear, isotropic medium, harmonic temporal variation of field ($e^{-i\omega t}$) and by neglecting displacement current, the MT responses can be described by the Maxwell equation.[19]

$$\nabla \times \vec{E} = i\omega\mu_0\vec{H} \quad (1)$$

$$\nabla \times \vec{H} = \sigma\vec{E} \quad (2)$$

$\vec{E}$ and $\vec{H}$ are the electric and magnetic field respectively, ω is the angular frequency,μ_0 is the magnetic permeability of free space and σ is the electrical conductivity.

For separate electric and magnetic field components, the Maxwell's equation (1) and (2) can be written on frequency domain as:

$$\nabla^2\vec{E}(r,\omega) = -i\sigma\mu\omega\vec{E}(r,\omega) \quad (3)$$

$$\nabla^2\vec{H}(r,\omega) = -i\sigma\mu\omega\vec{H}(r,\omega) \quad (4)$$

The diffusion factor, describing the skin depth for homogeneous medium can be approximated to,

$$\delta(\omega) \approx 503\sqrt{\sigma T}(meter) \quad (5)$$

On the earth's surface the linear relationship between the horizontal components of the MT fields can be written in terms of impedance tensor as,

$$E = Z.H \quad (6)$$

Where E, H and Z are all complex quantities, the complex impedance $\vec{Z}$ is the function of frequency, electrical properties of the subsurface, orientation of measured axes and of measured MT site. The complex transfer function Z is usually represented by its amplitude and phase. The apparent resistivity and phase are defined in terms of the transfer function as,

$$\rho_a(\omega) = \frac{1}{\mu_0\omega}|Z|^2 \quad (7)$$

$$\boldsymbol{\varphi} = \mathbf{tan^{-1}}\left(\frac{\mathbf{Im(Z)}}{\mathbf{Re(Z)}}\right) \quad (\mathbf{8})$$

Transverse Magnetic and Transverse Electric Polarization Modes:

In two-dimensional (2D) earth, the Maxwell's equations are decoupled into two modes of polarization. Transverse electric (TE-mode) corresponding to the electric field component being transverse to the z-direction and parallel to strike. Same as, transverse magnetic (TM-mode) of polarization is one in which magnetic field component is transverse to z-direction and parallel to the strike.[19,20] The MT response including impedance, apparent resistivity and phase at each MT period are calculated for TE and TM-mode.

TE-mode,

$$Z_{xy} = \frac{E_x}{H_y}$$

$$\rho_{xy} = \frac{1}{\omega\mu}\left|z_{xy}\right|^2$$

$$\varphi_{xy} = \tan^{-1}\left(\frac{Im(Z_{xy})}{Re(Z_{xy})}\right)$$

For TM-mode,

$$Z_{yx} = \frac{E_y}{H_x}$$

$$\rho_{yx} = \frac{1}{\omega\mu}\left|Z_{yx}\right|^2$$

$$\varphi_{yx} = \tan^{-1}\left(\frac{Im(Z_{yx})}{Re(Z_{yx})}\right)$$

TWO-DIMENSIONAL MT FORWARD MODELING

Inhomogeneous two-dimensional (2D) geo electromagnetic perturbation has been modeled using the FDM.[21] Several researchers have since expanded the FDM to include 3D modelling.[22] Since numerous elements have been added to the finite difference modeling technique to increase its adaptability. Weaver and Rastogi provide an extensive discussion on EM/MT field computation using FDM.[23,24] The FDM for 2D inversion of geo electromagnetic data obtained over a 2D flat earth model was further developed, and the resulting code is known as EM2INV.[24]

In present research work, the 2D forward and inversion modeling code EM2INVbased on FDM is extended to compute MT forward modeling responses over undulating topography. The modified algorithm has been tested over published models in literature and responses are compared. The modified codes also applied to analyze the distortion effects in MT response due to undulating topography in Himalayan region at various periods in the range from 0.001 sec. to 121 sec. (Figure 1).

VALIDATION OF ALGORITHM AND THEIR RESULTS

Model-I

A co-sinusoidal hill model of 100 Ω-m homogeneous half space has been considered.[15] The height of hill model has been considered from 100 m to 500 m with 2400 m wide at the base. Apparent resistivity and phase are computed at period 0.1 sec. and the result are compared with published result (Figure: 2) for both TE- and TM-mode data. It is noted that results from the FEM and FDM are

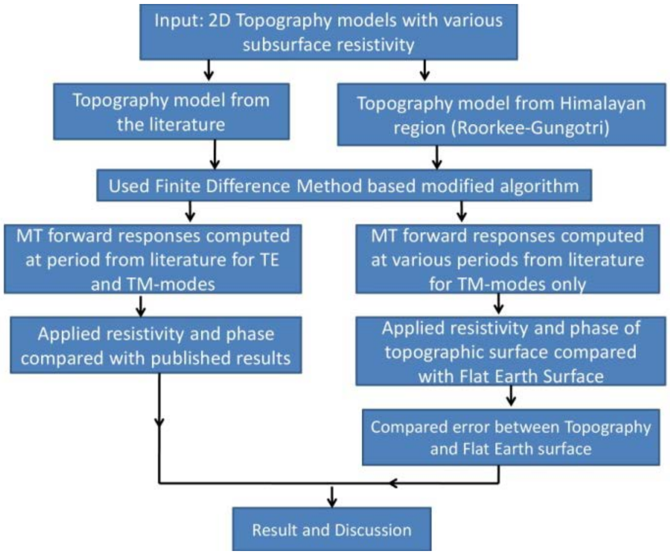

Figure 1. Experimental procedure outline

roughly comparable. Due to FEM and FDM's discrimination procedures, the slight variations in both responses can be seen. Figure 3 shows the computed MT responses over different hill height at the period 0.1 sec. for both TE- and TM-mode data. It is observed that as the height of hill increased, apparent resistivity and phase are more distorted in TM-mode as compared to TE-mode. The TM-mode responses become more distorted if the angle of inclination (4.76, 9.46, 18.43, 22.61, and 14.03), or the height of the hill increased.

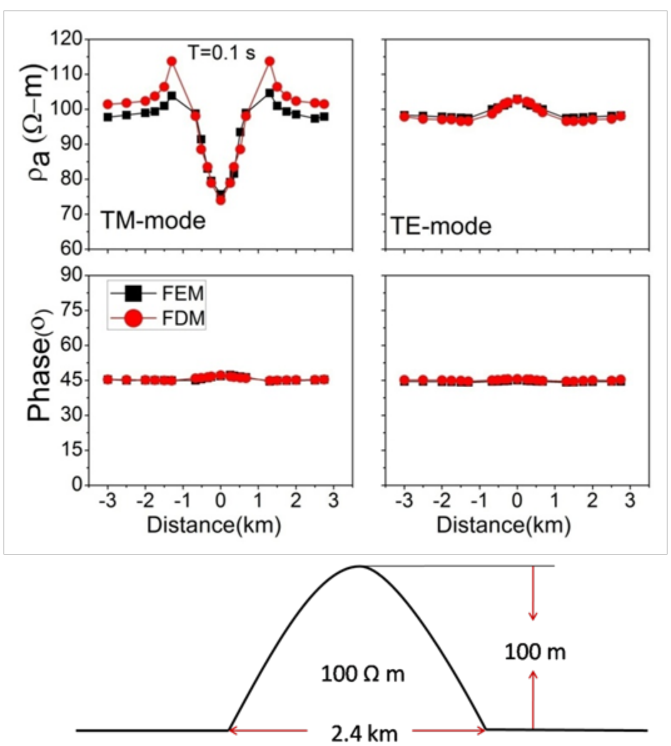

Figure 2. Comparison of the TM and TE modes response of the FDM with FEM of Wannamaker et al., 1986[7]

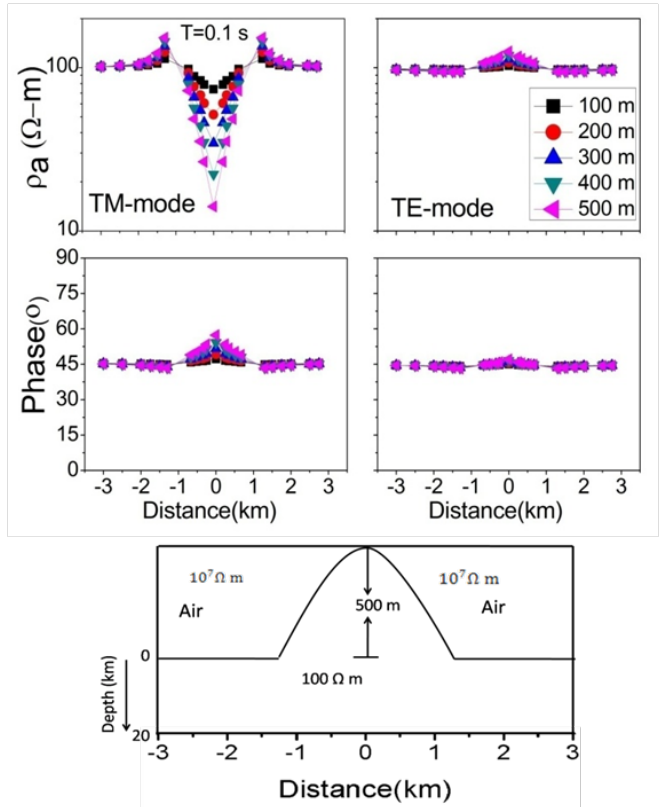

Figure 3. MT responses for cosinusoidal hill model of100 Ω-m homogeneous half space with 100 m to 500 m hill height at 0.1 s.

Model II:

A second model considered which deliberate of a resistivity 10000 Ω-m block about 1 km thick, which is embedded in a 500 Ω-m homogeneous half space.[25] This model is similar to mountainous region and the topography was as associated with both 500 Ω-m and 10000 Ω-m earth resistivity. MT responses computed at period 0.1 sec. for TM-mode at topography and flat Earth surface. The apparent resistivity and phase for topography and the flat Earth surface are shown in (Figure 4), and they are compared to reported topography responses with FEM. A modified methodology can be employed for mountainous regions like the Himalaya because the MT responses based on the FDM and FEMs are very closely approximations. The relative error between topographical responses (TR) and flat earth responses (FER) at six different periods is also calculated and are given in Table 1. It has been discovered that the MT responses are more distorted at places that are close to valleys and steep hills. In order to analyses the period influence on TM responses brought on by topography, MT responses are computed at 6 different periods (figure 5) and compared with FERs. It is demonstrated that the MT responses are more distorted at period of 100 sec.

Model-III

Himalayan topography is very complex as it contains hills, valleys and ramps. A two-dimensional topography model of Roorkee to Gangotri section is taken to compute MT responses at 32 sites. To compute MT forward modeling responses over topography surface in Roorkee-Gangotri Section, the input model

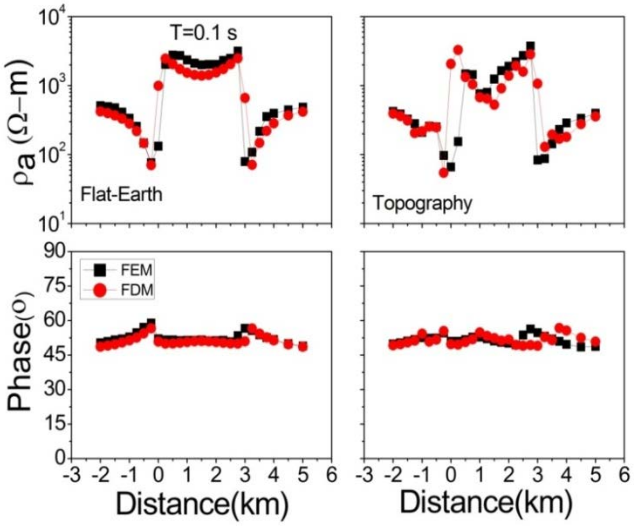

Figure 4. Comparison of the TM mode response of the FDM with FEM of Chouteau and Bouchard, 1988[25]

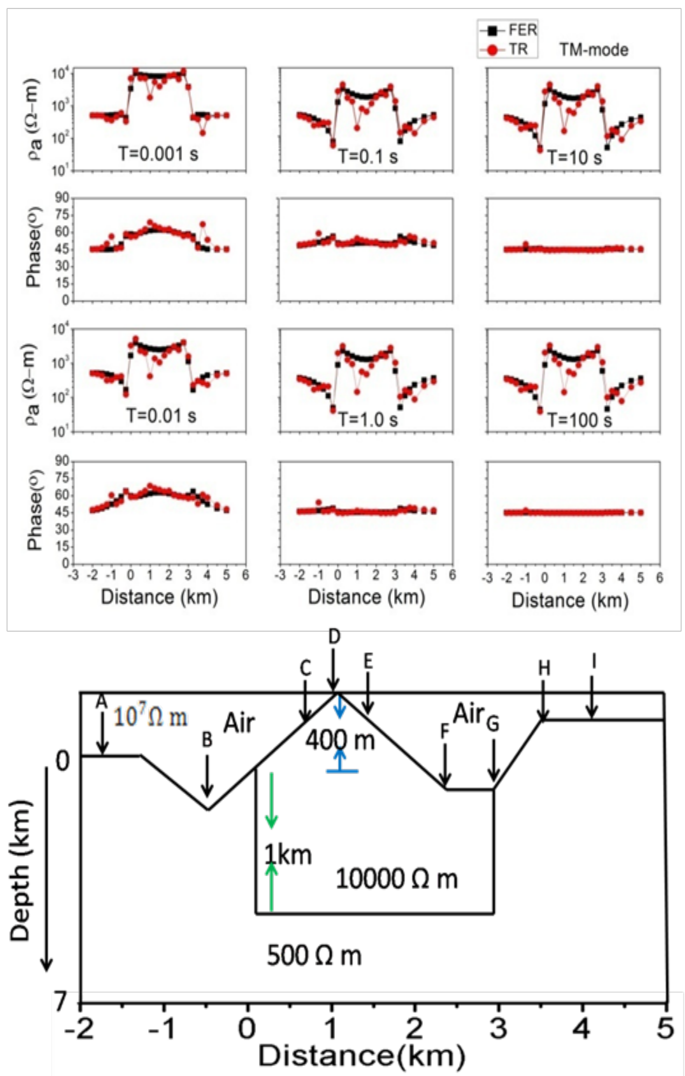

Figure 5. TM response of topography model and flat earth model at 6 different periods

Table1. Relative error between flat earth responses and Topography distortion at various periods for model 2

Period= 0.001 s				Period= 0.01 s			Period= 0.1 s		
Obs. Point	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)
A	502.9	506.24	0.007	509.12	482.65	0.052	399.34	361.34	0.095
B	531.29	605.79	0.140	294.2	414.92	0.410	146.63	248.02	0.691
C	8572.2	7037.4	0.179	2875.1	1984.3	0.310	1732.1	1039.4	0.400
D	8335.2	1805.1	0.783	2635	413.01	0.843	1534.9	175.54	0.886
E	8222.4	5467.6	0.335	2506.5	1371.7	0.453	1425.8	646.18	0.547
F	8571.7	9159.4	0.069	2887	3070.4	0.064	1741	1941.3	0.115
G	3829.9	3748.2	0.021	1123.7	1579.8	0.406	661.38	1065.5	0.611
H	431.56	449.31	0.041	165.76	230.58	0.391	71.215	129.21	0.814
I	516.89	433.61	0.161	442.85	232.39	0.475	282.91	122.57	0.567
Period= 1.0 s				Period= 10 s			Period= 100 s		
Obs. Point	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)
A	346.79	310.71	0.104	337.79	305.47	0.096	335.44	304.34	0.093
B	111.06	208.61	0.878	104.01	205.09	0.972	102.04	204.4	1.003
C	1610.2	942.12	0.415	1623.4	955.06	0.412	1630.2	961.12	0.410
D	1418.8	144.86	0.898	1428.8	142.73	0.900	1434.3	142.39	0.901
E	1312.3	562.15	0.572	1320.3	562.9	0.574	1325.1	564.33	0.574
F	1618.6	1890.6	0.168	1631.9	1951.1	0.196	1638.8	1973.9	0.204
G	592.66	1025.4	0.730	589.86	1050.5	0.781	589.94	1060.2	0.797
H	51.038	104.79	1.053	46.978	100.88	1.147	45.841	99.826	1.178
I	232.89	87.795	0.623	223.72	80.25	0.641	221.22	78.086	0.647

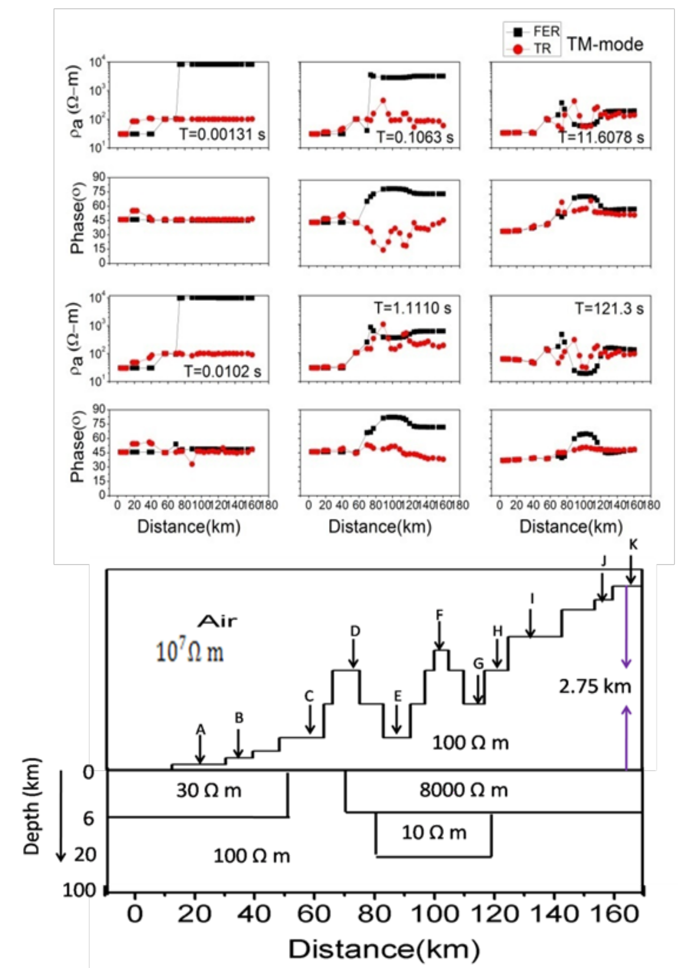

Figure 6. MT responses of topography and flat earth surface of synthetic field data at different 6 periods

is prepared from two-dimensional (2D) inverted geoelectrical resistivity model.[26] The distortion effects in MT responses are analyzed at 32 sites at different periods (0.0013 sec., 0.0102 sec., 0.1063 sec,1.1110 sec.,11.6078 sec. and 121.30 sec.) in (Figure 6). Table 2 shows the relative errors between flat earth and topography responses at all six periods. It is observed that the distortion effects are more significant at periods 121.3 sec. and the sites which are located on top of hill and in valley.

Discussion

It has been observed from the previous studies that outcomes of FEM and FDM are generally comparable.[7] Because of FEM and FDM's discrimination methods, the slight variations in the two responses should be visible. A finite difference method based modified algorithm is used for MT responses in mountainous area like the Himalaya. Figure 3 shows the computed MT responses over various slope levels at the period 0.1 sec. for both TE-and TM-mode observation. It was observed that as the height of slope increased, apparent resistivity and phase are more distorted in TM-mode in comparison with TE-mode. The TM-mode responses become more distorted when the height of slope (increasing angles of slope: 4.76, 9.46, 18.43, 22.61, and 14.03 what is this) is increased.

Table 2: Relative error between flat earth and Topography distortion responses at various periods for model 4

	Period= 0.00131 s			Period= 0.0102 s			Period= 0.1063 s		
Obs. Sites	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)
A	30.207	84.407	1.794	30.322	48.634	0.604	30.378	35.471	0.168
B	30.207	107.34	2.553	30.322	73.689	1.430	30.378	44.466	0.464
C	100.62	99.906	0.007	100.84	99.899	0.009	100.75	100.55	0.002
D	8222.1	100.19	0.988	9723.2	102.9	0.989	3507.3	91.012	0.974
E	8233.8	100.8	0.988	10096	83.211	0.992	2826.5	452.69	0.840
F	8233.8	99.978	0.988	10111	100.3	0.990	2807.5	93.13	0.967
G	8233.7	100.21	0.988	10036	95.191	0.991	2882	159.83	0.945
H	8234.6	100.23	0.988	9929	100.67	0.990	3009.3	97.656	0.968
I	8235.2	99.995	0.988	9780.3	100.37	0.990	3193.9	86.161	0.973
J	8235.2	99.943	0.988	9778.7	100.59	0.990	3199.9	85.131	0.973
K	8235.2	102.16	0.988	9778.7	91.085	0.991	3199.9	59.977	0.981
	Period= 1.111 s			Period= 11.6078 s			Period= 121.3 s		
Obs. Point	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)	ρ_{FER}	ρ_{TR}	Relative error (ρ)
A	30.007	31.532	0.051	33.632	33.883	0.007	57.453	57.758	0.005
B	30.008	34.075	0.136	32.868	34.494	0.049	46.272	48.283	0.043
C	101.41	101.83	0.004	93.55	97.616	0.043	120.36	122.69	0.019
D	781	139.15	0.822	371.11	45.009	0.879	441.09	71.918	0.837
E	351.85	996.31	1.832	65.457	428.77	5.550	23.869	287.18	11.032
F	338.2	134.42	0.603	58.13	54.027	0.071	18.887	30.429	0.611
G	382.6	492.13	0.286	80.595	265.19	2.290	34.177	172.52	4.048
H	452.71	258.53	0.429	122.03	141.8	0.162	76.154	92.507	0.215
I	563.95	206.41	0.634	188.01	128.71	0.315	149.44	86.836	0.419
J	570.07	162.29	0.715	191.9	132.9	0.307	129.32	88.959	0.312
K	570.08	182.42	0.680	192.37	140.01	0.272	126.99	93.39	0.265

The apparent resistivity and phase for topography and the flat Earth responses are shown in (Figure 4), and they are compared with reported topography responses with finite element method (FEM). The relative error between topography responses (TR) and flat earth responses (FER) at six distinct periods is additionally computed and are given in Table 1. It has been found that the MT responses are more distorted at places that are near valleys and on steep slopes. At periods of 10 seconds and 100 seconds, the distortion in apparent resistivity and phase caused by undulating topography is investigated. MT responses are computed at 6 different periods (figure 5) and compared with FERs in order to analyses the period influence on TM responses caused by topography. It is showed that the MT responses are more distorted at period 100 sec for the sites which are at top of the hill.

A two-dimensional topography model of Roorkee to Gangotri section is taken to compute MT responses at 32 sites. To compute MT forward responses over 2D topography earth's surface in Roorkee-Gangotri section, the input model is prepared from two-dimensional (2D) inverted geoelectrical resistivity model.[9] Figure 6 show the distortion effects in MT responses at 32 sites for six different periods (0.0013 sec., 0.0102 sec., 0.1063 sec,1.1110 sec., 11.6078 sec. and 121.30 sec.). It has been observed that the distortion impacts are more prominent at periods 121.3 sec. and the sites which are placed near or on top of the hill and in valley.

Table 2 shows the relative error between flat earth and topography responses of few sites at six different periods. The relative error is high for sites which are near or on top of the hills at periods 0.0013 sec., 0.0102 sec. and 0.1063 sec. due to high vertical resistivity contrasts in subsurface resistivity and enormous raise in topography.

Conclusion

Apparent resistivity and phase are computed over undulating 2D topography models. MT responses are computed by extending numerically finite difference techniques used in forward modeling algorithm over 2D topographic surfaces. Two topographical models that have been published in the literature are used to test the algorithm's correctness. The computed results are in good agreement with findings that have been published using other numerical techniques. At periods of 10 seconds and 100 seconds, the distortion in apparent resistivity and phase caused by undulating topography is examined. After examining the relative inaccuracy between flat earth and topographical responses, it is observed that apparent resistivity and phase are more distorted at sites that are near or on top of hills. A theoretical analysis of topography's impact on MT responses is also taken into account over the Himalayan topography model (Roorkee-Gangotri section). Six different periods are used to analyze the distortion caused by the complicated topography of the Himalayas; the distortion effect is most pronounced at times of 121.3 sec. Relative error is high at periods 0.0013 sec., 0.0102 sec. and 0.1063 sec. due to high vertical resistivity contrasts in subsurface resistivity. It is also observed that the relative error is low at periods 1.1110 sec., 11.6078 sec. and 121.3 sec. and distortion in MT responses is reflected more at those sites which are near or on top of the hill and in the vicinity of valley along the profile at above mention periods. Analysis and topographical effect removal are important for the precise interpretation of MT data.

Conflict of Interest

Authors declare no conflict of interest.

REFERENCES

1. L. Cagniard. Basic theory of the magneto-telluric method of geophysical prospecting. *Geophysics* **1953**, 18 (3), 605–635.
2. V.P. Maurya, R.K. Singh, Shalivahan, B.B. Bhattacharya. Magnetotelluric exploration of a deposit scale prospecting over a proterozoic volcanics, Eastern India. *J. Appl. Geophys.* **2018**, 159, 666–677.
3. P.K. Patro. Magnetotelluric Studies for Hydrocarbon and Geothermal Resources: Examples from the Asian Region. *Surv. Geophys.* **2017**, 38 (5), 1005–1041.
4. D. Kumar, A. Singh, M. Israil. Necessity of Terrain Correction in Magnetotelluric Data Recorded from Garhwal Himalayan Region, India. *Geosciences* **2021**, 11 (11), 482.
5. S. Kumar, P.K. Patro, B.S. Chaudhary. Three dimensional topography correction applied to magnetotelluric data from Sikkim Himalayas. *Phys. Earth Planet. Inter.* **2018**, 279, 33–46.
6. C. Lin, S. Zhong, E. Auken, et al. The effects of 3D topography on controlled-source audio-frequency magnetotelluric responses. *Geophysics* **2018**, 83 (2), WB97–WB108.
7. P.E. Wannamaker, J.A. Stodt, L. Rijo. Two-dimensional topographic responses in magnetotellurics modeled using finite elements. *Geophysics* **1986**, 51 (11), 2131–2144.
8. G.R. Jiracek. Near-surface and topographic distortions in electromagnetic induction. *Surv. Geophys.* **1990**, 11 (2–3), 163–203.
9. E.M. Wescott, V.P. Hessler. The effect of topography and geology on telluric currents. *J. Geophys. Res.* **1962**, 67 (12), 4813–4823.
10. A.S. Faradzhev, K.K. Kakhramanov, G.A. Sarkisov, N.E. Khalilova. On effects of terrain on magnetotelluric sounding (MTS) and profiling (MTP). *Izv. Earth Phys.* **1972**, 5, 329–330.
11. T. Harinarayana, S.V.S. Sarma. Topographic effects on telluric field measurements. *Pure Appl. Geophys.* **1982**, 120 (4), 778–783.
12. M.J. Nam, H.J. Kim, Y. Song, T.J. Lee, J.H. Suh. Three-dimensional topography corrections of magnetotelluric data. *Geophys. J. Int.* **2008**, 174 (2), 464–474.
13. W. Sarakorn, C. Vachiratienchai. Hybrid finite difference–finite element method to incorporate topography and bathymetry for two-dimensional magnetotelluric modeling. *Earth, Planets Sp.* **2018**, 70 (1), 103.
14. X. Zhu, J. Liu, Y. Cui, C. Gong. An efficient parallel algorithm for 3D magnetotelluric modeling with edge-based finite element. *Comput. Geosci.* **2021**, 25 (1), 1–16.
15. R.L. Mackie, T.R. Madden, P.E. Wannamaker. Three-dimensional magnetotelluric modeling using difference equations - theory and comparisons to integral equation solutions. *Geophysics* **1993**, 58 (2), 215–226.
16. C. Chen, M. Kruglyakov, A. Kuvshinov. Advanced three-dimensional electromagnetic modelling using a nested integral equation approach. *Geophys. J. Int.* **2021**, 226 (1), 114–130.
17. Y. Usui, Y. Ogawa, K. Aizawa, et al. Three-dimensional resistivity structure of Asama Volcano revealed by data-space magnetotelluric inversion using unstructured tetrahedral elements. *Geophys. J. Int.* **2017**, 208 (3), 1359–1372.
18. M.J. Nam, H.J. Kim, Y. Song, T.J. Lee, J.H. Suh. Three-Dimensional Magnetotelluric Modeling Including Surface Topography. In *67th EAGE Conference & Exhibition*; European Association of Geoscientists & Engineers, **2005**; Vol. 67th Europ, pp 2765–2769.
19. X. Bin, L. Tian-Ya, C. Long-Wei, et al. Influence of complex topography on magnetotelluric-observed data using three-dimensional numerical simulation: A case from Guangxi area, China. *Appl. Geophys.* **2020**, 17 (4), 601–615.
20. A. Martí, P. Queralt, J. Ledo, C. Farquharson. Dimensionality imprint of electrical anisotropy in magnetotelluric responses. *Phys. Earth Planet. Inter.* **2010**, 182 (3–4), 139–151.
21. F. W. Jones, L. J. Pascoe. A General Computer Program to Determine the Perturbation of Alternating Electric Currents in a Two-Dimensional Model of a Region of Uniform Conductivity with an Embedded Inhomogeneity. *Geophys. J. R. Astron. Soc.* **1971**, 24 (1), 3–30.
22. X. Tong, Y. Guo, W. Xie. Finite Difference Algorithm on Non-Uniform Meshes for Modeling 2D Magnetotelluric Responses. *Algorithms* **2018**, 11 (12), 203.
23. J.T. Weaver. Mathematical methods for geo-electromagnetic induction; Taunton, Somerset, England: Research Studies Press; New York: Wiley, **1994**; Vol. 7.
24. M. Kordy, P. Wannamaker, V. Maris, E. Cherkaev, G. Hill. 3-D magnetotelluric inversion including topography using deformed hexahedral edge finite elements and direct solvers parallelized on SMP computers - Part I: Forward problem and parameter Jacobians. *Geophys. J. Int.* **2016**, 204 (1), 74–93.
25. M. Chouteau, K. Bouchard. Two-dimensional terrain correction in magnetotelluric surveys. *Geophysics* **1988**, 53 (6), 854–862.
26. M. Israil, D.K. Tyagi, P.K. Gupta, S. Niwas. Magnetotelluric investigations for imaging electrical structure of Garhwal Himalayan corridor, Uttarakhand, India. *J. Earth Syst. Sci.* **2008**, 117 (3), 189–200.