22 Udem, S A and Cook, R A, *J. Virol*, 1984, 49, 57–65.
23 Portner, A and Murti, K G, *Virology*, 1986, 150, 469–478
24 Plowright, W, *Virol Monogr*, 1962, **3**, 29–30.
25 Kesari, K. V, Ph D Thesis, Indian Institute of Science, Bangalore, 1985
26 Lund, G A, Tyrrel, D L J, Bradley, R D and Scrabin, D. G, *J Gen Virol*, 1984, 65, 1535–1542.
27. Kumar, A M and Nayak, R, in *Contemporary Themes in Biochemistry* (eds. Kon, O, *et al*), ICSU Press, 1986, pp. 182–183
28 Andzhaparidze, O. G., Chaplygina, N. M, Bogomolova, N. N, Lottie, N D, Koptyaeva, I. B and Boriskin, Yu. S., *Arch. Virol.*, 1987, 95, 17–28
29 Andzhaparidze, O G, Boriskin, Yu S., Bogomolova, N. N and Lottie, N. D, *Arch Virol*, 1983, 75, 283–289.

ACKNOWLEDGEMENTS. We thank R. Rangeswaran for his expert assistance in electron microscopy. We also thank Bhuvaneshwari of Molecular Biophysics Unit for helping with the use of stereomicroscope This research was supported by a grant under the Molecular Virology Programme from the Department of Biotechnology, Government of India

Received 20 April 1994, revised accepted 11 July 1994

A study on the comparison of CSAMT and MT data

I. B. Ramaprasada Rao, Ram Raj Mathur and S. Srinivas

Centre of Exploration Geophysics, Osmania University, Hyderabad 500 007, India

Analysis of Controlled Source Audio Frequency Magneto Telluric (CSAMT) data is conventionally carried out using Cagniard resistivity under far field conditions. However, the near field response, which cannot be avoided in the field operations, differs considerably from the far field response. The discrepancy has been recognized the world over. In India the potential of CSAMT has not been exploited in its entirety. To bridge this gap on the Indian scene, a beginning has been made by studying the far field–near field discrepancies. The near field response in CSAMT for Vertical Magnetic Dipole (VMD) and Horizontal Electric Dipole (HED) is computed for homogeneous and two layer media. The critical frequency below which the near field conditions validity is studied, and the correction factor to make near field data look like far field data over a homogeneous medium discussed.

THE Controlled Source Audio-Frequency Magnetotelluric method (CSAMT)[1,2] is a frequency domain electromagnetic sounding technique with a fixed grounded electric dipole or horizontal loop (or a vertical magnetic dipole) as signal source. Stronger and stable signal, time invariance of the primary field polarization and its selectability confer a marked advantage for CSAMT over natural source methods (MT and AMT).

While two perpendicular horizontal components of electric and magnetic fields (E_x and H_y) are measured in scalar CSAMT, E_x, H_y, H_x and H_z components are measured in vector CSAMT. Usually five components (namely E_x, E_y, H_x, H_y and H_z) with two source polarizations are measured in Tensor CSAMT.

CSAMT results have been reported over sulphide targets[3], over massive sulphide body in Japan[4], over lead/zinc/silver deposit in Alaska[5], over uranium and sulphide/graphite targets[4], over base metals in Finland[6–8]. CSAMT measurements have been carried out by Uchida *et al.*[9] over a copper/lead/zinc deposit in Japan. CSAMT measurements have also been proved successful in the search for gold deposits in Japan[10].

CSAMT measurements have been carried out for geothermal exploration in USA[12], in Japan[4,13] and in Hawaii[14]. In petroleum exploration, CSAMT has been used for structural mapping[4,15–18].

CSAMT method proved effective in the investigations for groundwater quality[19–23], for structural analysis in mine planning[24], detecting voids in underground mines[25], mapping burn fronts in underground coal gasification and coal mine fires[24,26]. However, practically no study has been reported from India.

Far field and near field

Usually, if the transmitter receiver separation $r \ll \delta$ and the induction number $|kr| \ll 1$ (where $|k| = (\sigma\mu\omega)^{1/2}$ is the wave number of quasistatic case) it is known as the 'near field' zone. On the other hand if $r \gg \delta$, $|kr| \gg 1$ it is known as 'far field' zone.

The theory for the MT, AMT, AFMAG and VLF case is well-formulated since the source independence of the EM field is assumed[27]. However, in CSAMT as the receiver–transmitter separation becomes less than 3 skin depths (skin depth, $\delta = (2/\sigma\mu\omega)^{1/2}$ for quasistatic case) at low frequencies, the field becomes 'near field' rather than ‘far field’, and the transmitter acts more like a local EM source than as a magneto-telluric source[28]. The finite source problem has been considered by a number of authors[1,2,29–34].

A fairly detailed discussion of EM field component behaviour under these two asymptotic ranges is given by Kaufman and Keller[34].

Here we assess the far field and near field CSAMT resistivity over homogeneous and layered media using Vertical Magnetic Dipole (VMD) and Horizontal Electric Dipole (HED).

The study

The fundamental aspects of the electromagnetic fields in earth study consisting of Maxwell’s equations, wave equation, solution for a homogeneous earth, quasistatic and dielectric limits, wave number, etc, being well documented, the initial development is not duplicated here. Similarly, the mathematical development of the solution of Helmholtz equation over layered media is also not considered here. Instead, we have confined ourselves to the main study of the CSAMT apparent resistivity in this article.

Vertical magnetic dipole solution (homogeneous earth)

The EM field components of vertical magnetic dipole placed on the surface of the homogeneous earth can be written as[31–37]

$$E_\phi = (Mi\omega\mu/4\Pi r^2)e_\phi, \tag{1}$$

$$H_r = (M/4\Pi r^3)\, h_r, \tag{2}$$

$$H_z = (M/4\Pi r^3)\, h_z. \tag{3}$$

M is the magnetic moment of the dipole given by $M = I\,Sn$, I being the current in the loop, Sn the area enclosed by the loop, and n the number of turns.

The magnetic and electric numbers h_z, h_r and e_ϕ are introduced as[34,37]

$$h_z = \frac{2}{\breve{\xi}^2}[9 - e^{i\breve{\xi}}(9 - 9i\breve{\xi} - 4\breve{\xi}^2 + i\breve{\xi}^3)]. \tag{4}$$

$$h_r = -i\frac{\Pi}{2}\breve{\xi}^2\left[J_2\left(\frac{\breve{\xi}}{2}\right)H_2\left(\frac{\breve{\xi}}{2}\right) - J_1\left(\frac{\breve{\xi}}{2}\right)H_1\left(\frac{\breve{\xi}}{2}\right)\right]. \tag{5}$$

$$e_\phi = \frac{2}{\breve{\xi}^2}[-3 + e^{i\breve{\xi}}(3 - 3i\breve{\xi} - \breve{\xi}^2)]. \tag{6}$$

where $\breve{\xi} = \bar{k}r$; $\xi = |\breve{\xi}|$.

Far field response ($\mathbf{r} \gg \delta$; $|kr| \gg 1$)

In the far field, the magnetic and electric numbers can be written as[27]

$$h_z = -18i/|\xi^2|, \tag{7}$$

$$h_r = 6(1+i)/|\sqrt{2}\xi|, \tag{8}$$

$$e_\phi = 6i/\xi^2. \tag{9}$$

Thus in the far field, the real component of H_z and E_ϕ are zero. The imaginary components of h_z and e_ϕ decreases as $1/r^2$. The horizontal component H_r has equal real and imaginary components. The field components H_r and E_ϕ decrease as $1/r^4$ while the vertical field component H_z decreases as $1/r^5$. Thus in the far zone the field of a vertical magnetic dipole over a homogeneous earth remains practically horizontal and can be viewed as vertically incident plane wave. Solving for the far field wave impedance we have

$$Z = \frac{E_\phi}{H_r} = \sqrt{\frac{\mu\omega}{\sigma}}\, e^{\frac{-i\Pi}{4}},$$

and

$$\rho = \left(\frac{1}{\omega\mu}\right)\left|\frac{E_\phi}{H_r}\right|^2, \tag{10}$$

which is the same as the Cagniard’s resistivity equation[38] employed in MT, AMT and VLF under plane wave assumption.

Further, the magnetic field of the vertical magnetic dipole placed over a homogeneous earth is elliptically polarized, with the plane of polarization lying in a vertical plane passing through the dipole moment. The magnetic numbers of the major and minor axes of the ellipse are given by[36]

$$h_a = 6/kr, \tag{11}$$

$$h_b = \left(\frac{18}{\sqrt{2}}\right)\left(\frac{1}{kr}\right)^2. \tag{12}$$

Thus on obtaining the ratio of the major and minor axes of ellipse of polarization it is possible to obtain the resistivity of the homogeneous earth as

$$\rho = (\mu\omega r^2/4)\,(h_a/h_b).$$

Near field solution ($\mathbf{r} \ll \delta$; $|kR| \ll 1$)

The near field asymptotic solutions for the magnetic and electric numbers can be written as[36,37]

$$h_z = -1 - \frac{2\sqrt{2}}{15}\xi^3 + i\frac{\xi^2}{4}\left(1 - \frac{8\sqrt{2}}{15}\xi\right) \tag{13}$$

$$h_r = \frac{\xi^4}{16}\left(\ln\frac{\gamma\xi}{4} + \frac{1}{12}\right) + i\frac{\xi^2}{4}\left(1 - \frac{\Pi}{16}\xi^2\right) \tag{14}$$

$$e_\phi = \left(1 - \frac{\sqrt{2}}{15}\xi^3\right) + i\frac{\xi^2}{4}\left(1 - \frac{4\sqrt{2}}{15}\xi\right). \tag{15}$$

In view of the basic differences that exist between the 'far field' and 'near field' electromagnetic field component behaviour, significant discrepancies are introduced once the Cagniard resistivity (which is valid for MT and AMT and far field CSAMT) is computed for the near field measurements.

Figures 1 and 2 show the behavior of the CSAMT Cagniard apparent resistivity computed from equations (14) and (15) for near field measurements. The most common source effect is the distortion of apparent resistivity near the source. For a particular source–receiver separation **r** over a chosen ground resistivity, the computed resistivity approaches far field resistivity at a frequency designated by us as 'critical frequency' f_c. Below this frequency the apparent resistivity increases fairly linearly with decrease in frequency. Beyond this frequency, a distinct 'notch' or an 'under shoot', is recognized which is a decrease in resistivity below the true resistivity (Cagniard resistivity in case of homogeneous medium).

Vertical magnetic dipole (two layer earth)

Over a two-layer medium the magnetic and electric numbers depend on $q = 2h_1/r$, $\beta = \sigma_1/\sigma_2$ and $P_1 = |k_1 h_1|$, where h_1 and σ_1 are the thickness and conductivity of the first layer and σ_2 is the conductivity of the second layer.

The field due to a vertical magnetic dipole over a layered medium was studied extensively by several authors[35,39–51]. The near field solution ($k_1 \mathbf{r} \ll 1$, $k_2 \mathbf{r} \ll 1$) for small values of β are given by[34,36,47]

$$h_z = 1 + \left(\frac{P_1}{2}\right)^2 \left[1 + \left(\frac{\sigma_2}{\sigma_1} - 1\right)\left(\frac{1}{(1+q^2)^{1/2}}\right)\right], \tag{16}$$

$$e_\phi = 1 - \left(\frac{P_1}{2}\right)^2 \left[1 + \left(\frac{\sigma_2}{\sigma_1} - 1\right)(1+q^2)^{1/2} - q\right], \tag{17}$$

$$h_r = \left(\frac{P_1}{2}\right)^2 \left[\frac{\sigma_2}{\sigma_1} - \left(\frac{\sigma_2}{\sigma_1} - 1\right)\frac{q}{(1+q^2)^{1/2}}\right], \tag{18}$$

where $P_1 = |k_1 r|$ and $q = 2h_1/r$ as $h_1 \to \infty$, $q \to \infty$ and the above equations reduce to

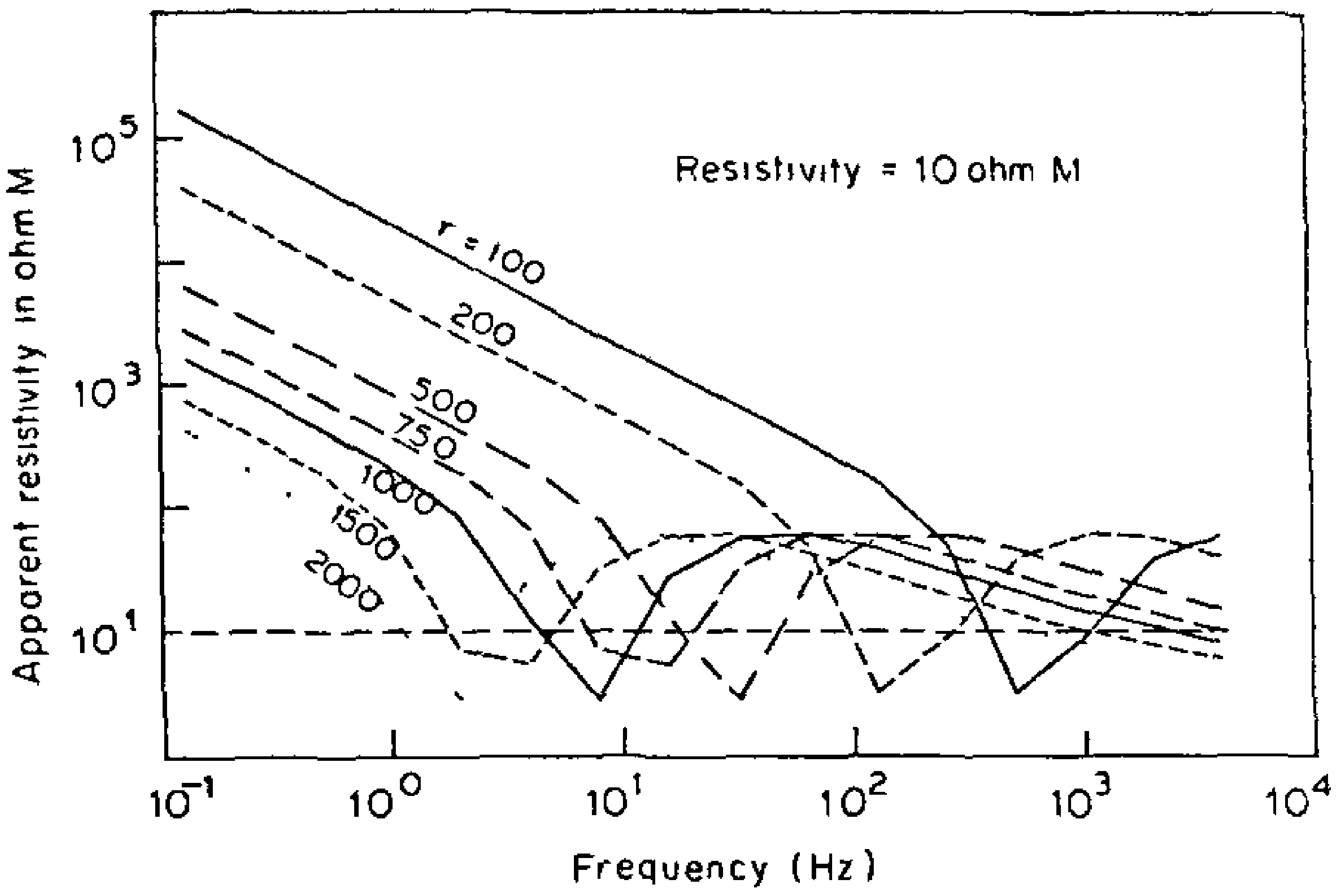

Figure 1. Homogeneous medium CSAMT response (VMD source)

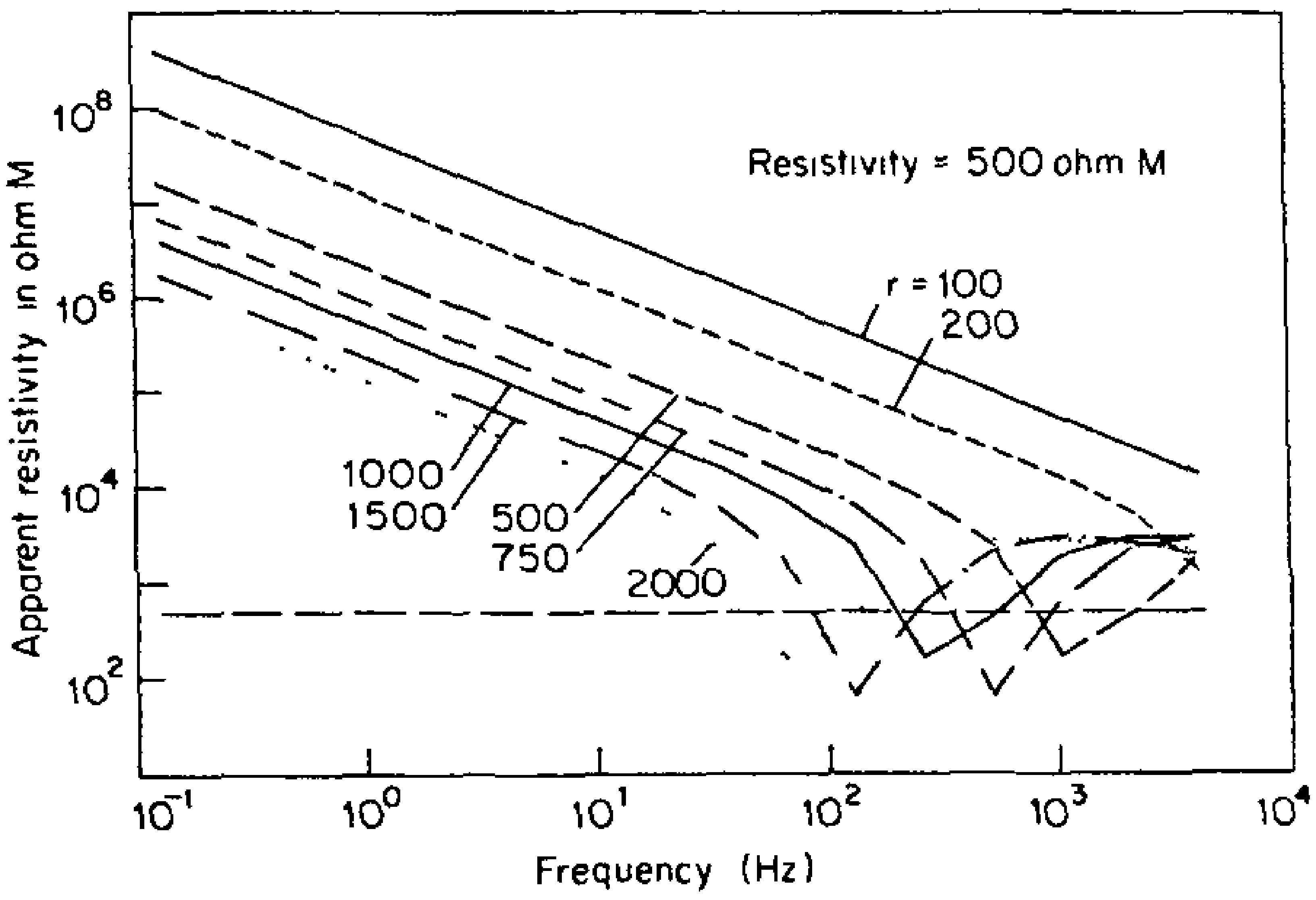

Figure 2. Homogeneous medium CSAMT response (VMD source)

$$e_\phi = 1 - (P_1/2)^2, \tag{19}$$

$$h_z = 1 + (P_1/2)^2, \tag{20}$$

$$h_r = (P_1/2)^2 (\sigma_2/\sigma_1). \tag{21}$$

The field components over a homogeneous medium [equations (1.153), (1.157) and (1.163) for $n = 4$ on pages 37, 38 and 40 of Kaufman and Keller[34]] coincide with equations (19) to (21).

In Figure 3, homogeneous medium Cagniard resistivity is compared with two-layer Cagniard resistivity for large values of h. The near field values fully agree with the homogeneous earth solution in its limiting case as $h_1 \to \infty$, $q \to \infty$. However, beyond a certain frequency where the undershoots occur, the two solutions differ.

Figures 4 and 5 show the Cagniard resistivity over a two-layer medium for q and β values mentioned in the respective figures within the frequency band of 0.125 to 4096 Hz.

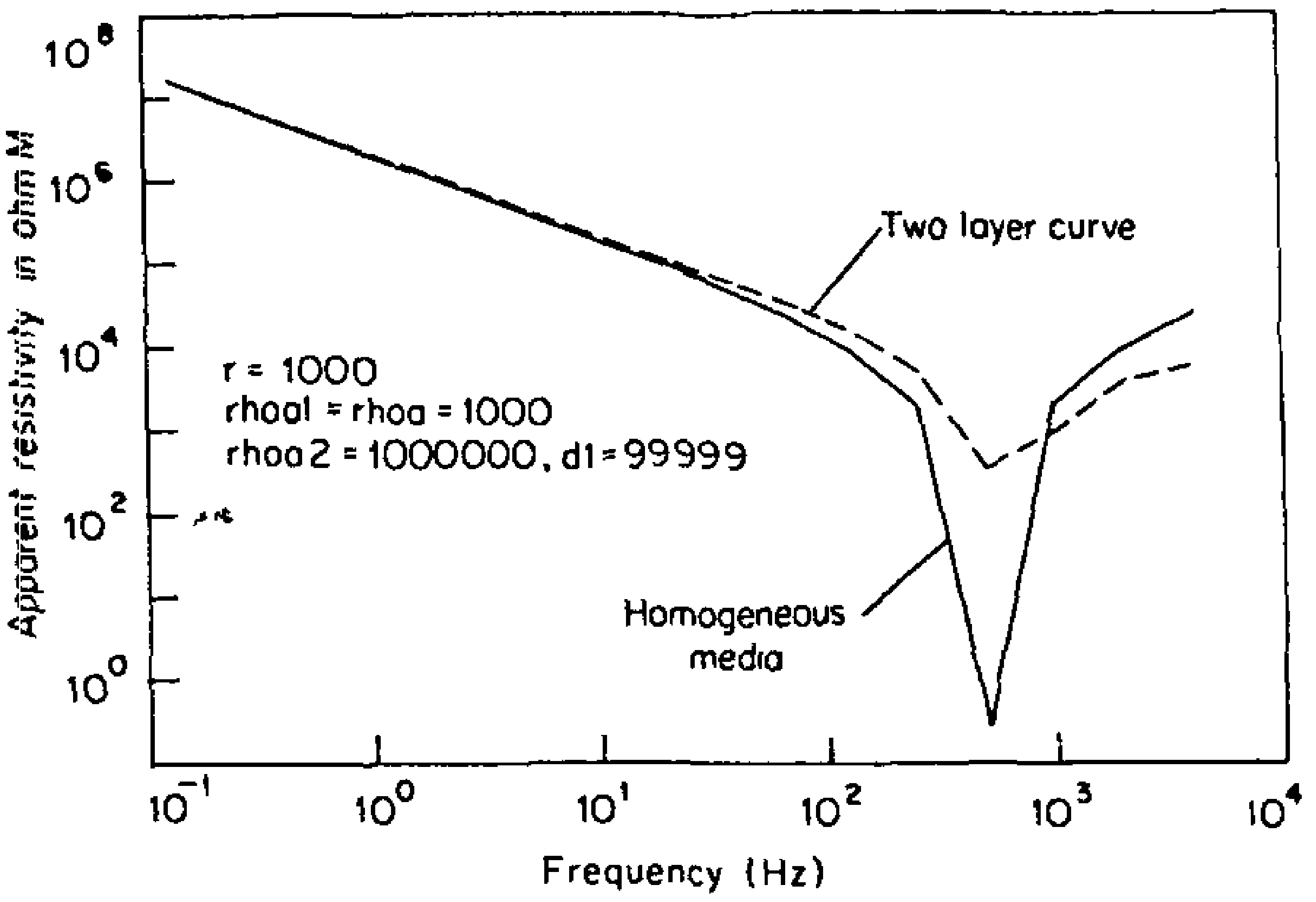

Figure 3. CSAMT response (VMD source)

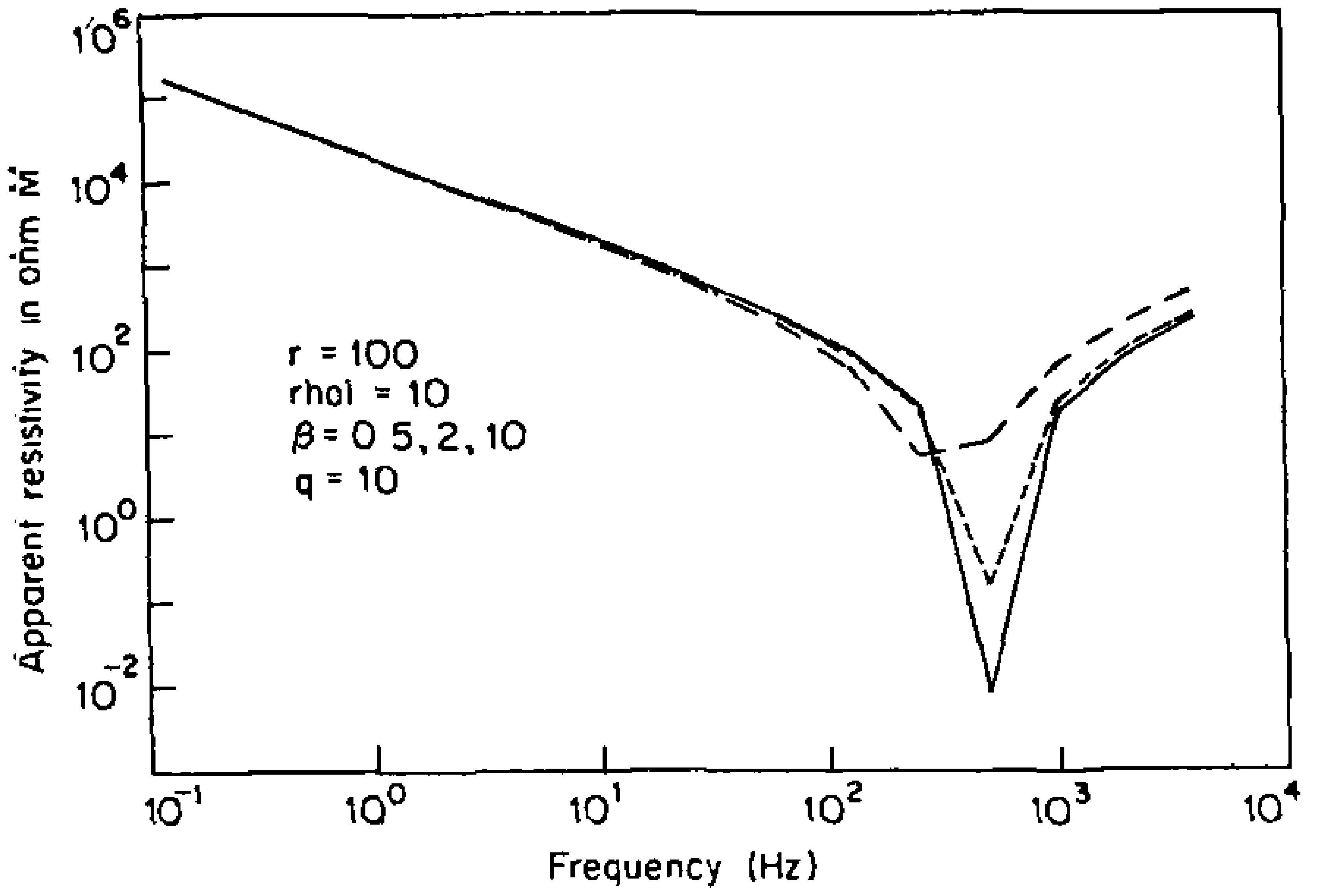

Figure 4. Two-layer medium CSAMT response (VMD source)

Horizontal electric dipole solution (homogeneous earth)

The electromagnetic fields due to grounded cable over a layered medium have been exensively studied by different authors[30, 33–35, 48, 50–55].

The field components can be written as[34, 37]

$$h_x = \frac{xy}{r^2} i \frac{\pi}{2} \bar{\xi}^2 \left[J_1\left(\frac{\bar{\xi}}{2}\right) H_2\left(\frac{\bar{\xi}}{2}\right) + J_2\left(\frac{\bar{\xi}}{2}\right) H_1\left(\frac{\bar{\xi}}{2}\right) \right], \quad (22)$$

$$h_y = -i\pi \left\{ J_1\left(\frac{\bar{\xi}}{2}\right) H_1\left(\frac{\bar{\xi}}{2}\right) - \frac{\bar{\xi}^2}{y} 2r^2 \right.$$
$$\left. \times \left[J_1\left(\frac{\bar{\xi}}{2}\right) H_2\left(\frac{\bar{\xi}}{2}\right) + J_2\left(\frac{\bar{\xi}}{2}\right) H_1\left(\frac{\bar{\xi}}{2}\right) \right] \right\}, \quad (23)$$

$$h_z = -2y / r\bar{\xi}^2 \left[3 - e^{i\bar{\xi}} (3 - 3i\bar{\xi} - \bar{\xi}^2)\right], \quad (24)$$

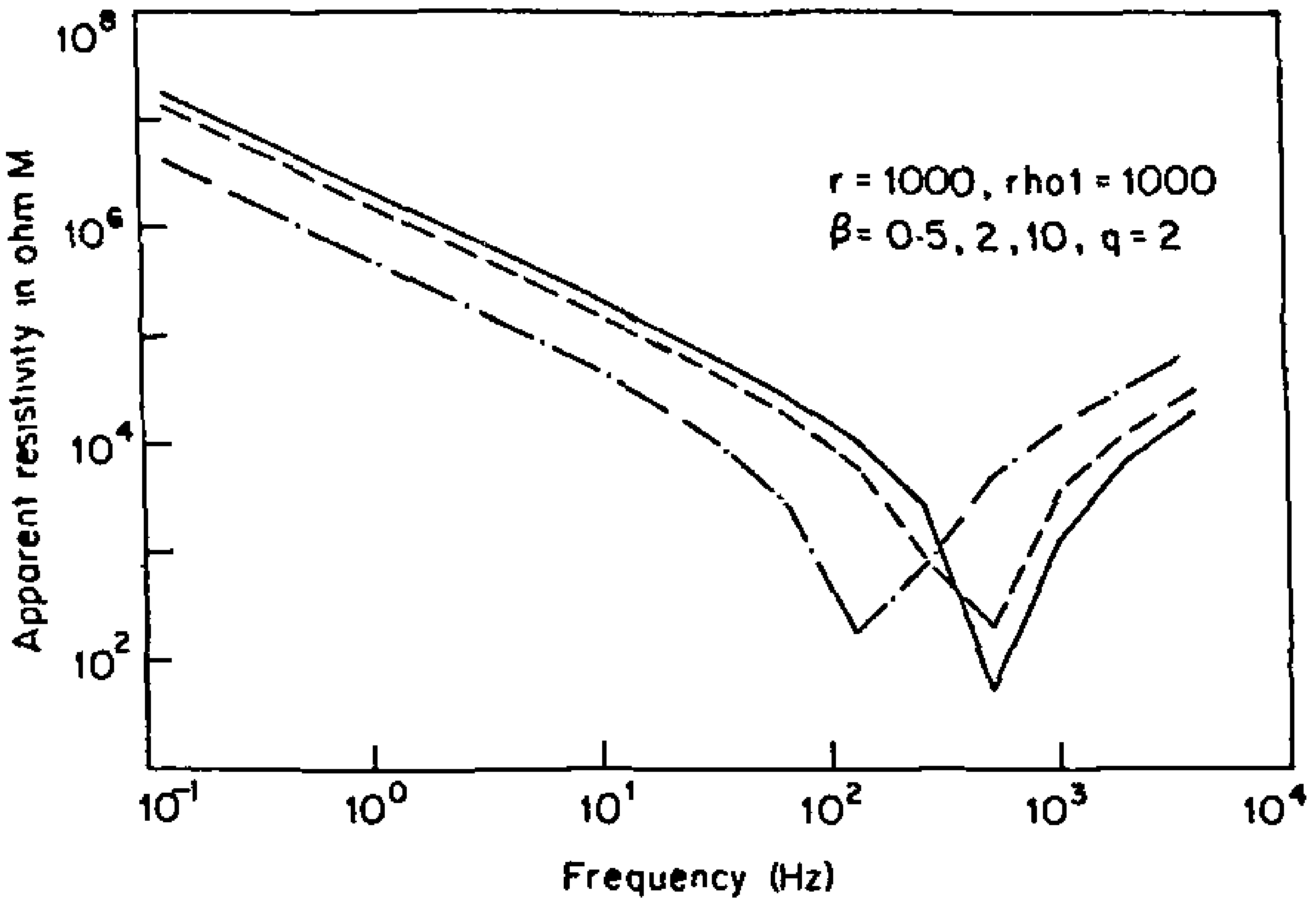

Figure 5. Two-layer medium CSAMT response (VMD source).

$$e_x = 6(x^2/r^2) - 4 + 2e^{i\bar{\xi}}(1 - i\bar{\xi}), \quad (25)$$

$$e_y = 6xy/r^2, \quad (26)$$

$$e_x = (-i\pi x/r)\bar{\xi}^2 J_1(\bar{\xi}/2) H_1(\bar{\xi}/2), \quad (27)$$

where $\bar{\xi} = \bar{k}r; \xi = |\bar{\xi}|$.

J_n and H_m represent modified Bessel functions of the nth order. Introducing the electric and magnetic numbers for electric dipole as $E_i = (P/4\pi r^3 \sigma_1)e_i$ and $H_i = (P/4\pi r^2)h_i$, $P = I.\,dl$, where dl is the length of the bipole and I is the current. The equations of the various components of the electrical and magnetic fields can be obtained from these equations by replacing the suffix i with the corresponding component (i.e. x or y or z).

Far zone response ($r \gg \delta$ *and* $|kr| \gg 1$)

The far zone components can be written as[37]

$$h_x = (6xy/r^2)(1 + i)/\sqrt{2}\,\xi, \quad (28)$$

$$h_y = \left(4 - 6\frac{x^2}{r^2}\right)\left(\frac{1+i}{\sqrt{2}\xi}\right), \quad (29)$$

$$h_z = 6i(y/r)(1/\xi^2), \quad (30)$$

$$e_x = 6(x^2/r^2) - 4, \quad (31)$$

$$e_z = -(3/2)(x/r), \quad (32)$$

where $\xi = (\sigma\omega\mu r)^{1/2}$.

The wave impedance in the far field zone is given by $Z = E_x/H_y$,

$$Z = (i\omega\mu/2)^{1/2} = (\mu\rho\omega)^{1/2} \cdot e^{i\pi/4}$$

and

$$\rho = \left(\frac{1}{\omega\mu}\right)\left|\frac{E_\phi}{H_r}\right|^2, \qquad (33)$$

which is the same as eq. (10) in the case of far field zone for vertical magnetic dipole. Thus the resistivities computed using the Cagniard equation using farfield solutions of either vertical magnetic dipole or horizontal electric dipole sources coincide with the plane wave solution used in MT, AMT and VLF.

Further the magnetic field is elliptically polarized and is practically horizontal in farfield zone.

Near field solution ($r \ll \delta$, $|kr| \ll 1$)

The near field solutions in Cartesian coordinate system are given by[36, 37]

$$h_x = \frac{xy}{r^2}\left[2 + \frac{\xi^2}{64}\left(\ln\frac{\gamma\xi}{4} - \frac{1}{3}\right) + i\frac{\xi^2}{8}\left(1 - \pi\frac{\xi^2}{32}\right)\right], \qquad (34)$$

$$h_y = -1 + \pi\frac{\xi^2}{32} + i\frac{\xi^2}{8}\left(\ln\frac{\gamma\xi}{4} - \frac{1}{4}\right), \qquad (35)$$

$$h_z = \frac{y}{r}\left[1 - \frac{\sqrt{2}}{15}\xi^3 + i\frac{\xi^4}{4}\left(1 - \frac{4\sqrt{2}}{15}\xi\right)\right], \qquad (36)$$

$$e_x = 6\frac{x^2}{r^3} - 2 - \frac{\sqrt{2}}{15}\xi^3 + i\xi^2\left(1 - \pi\frac{\xi^2}{32}\right), \qquad (37)$$

$$e_y = 6(xy/r^2), \qquad (38)$$

$$e_z = \frac{x}{r}\left[\frac{\xi^4}{8}\left(\ln\frac{\gamma\xi}{4} - \frac{1}{4}\right) - i\xi^2\left(1 - \pi\frac{\xi^2}{32}\right)\right]. \qquad (39)$$

The Cagniard resistivity for collinear configuration computed using near field solution is presented in Figures 6 and 7 along with the farfield Cagniard resistivity.

The general behaviour of the non-plane wave effects on the resistivity computed agrees well with that of the vertical magnetic dipole fields.

From the above discussion it can clearly be observed that the non-plane wave effects for the 'near zone' in the CSAMT method cannot be neglected and there is a significant departure for the far field conditions of the MT solution.

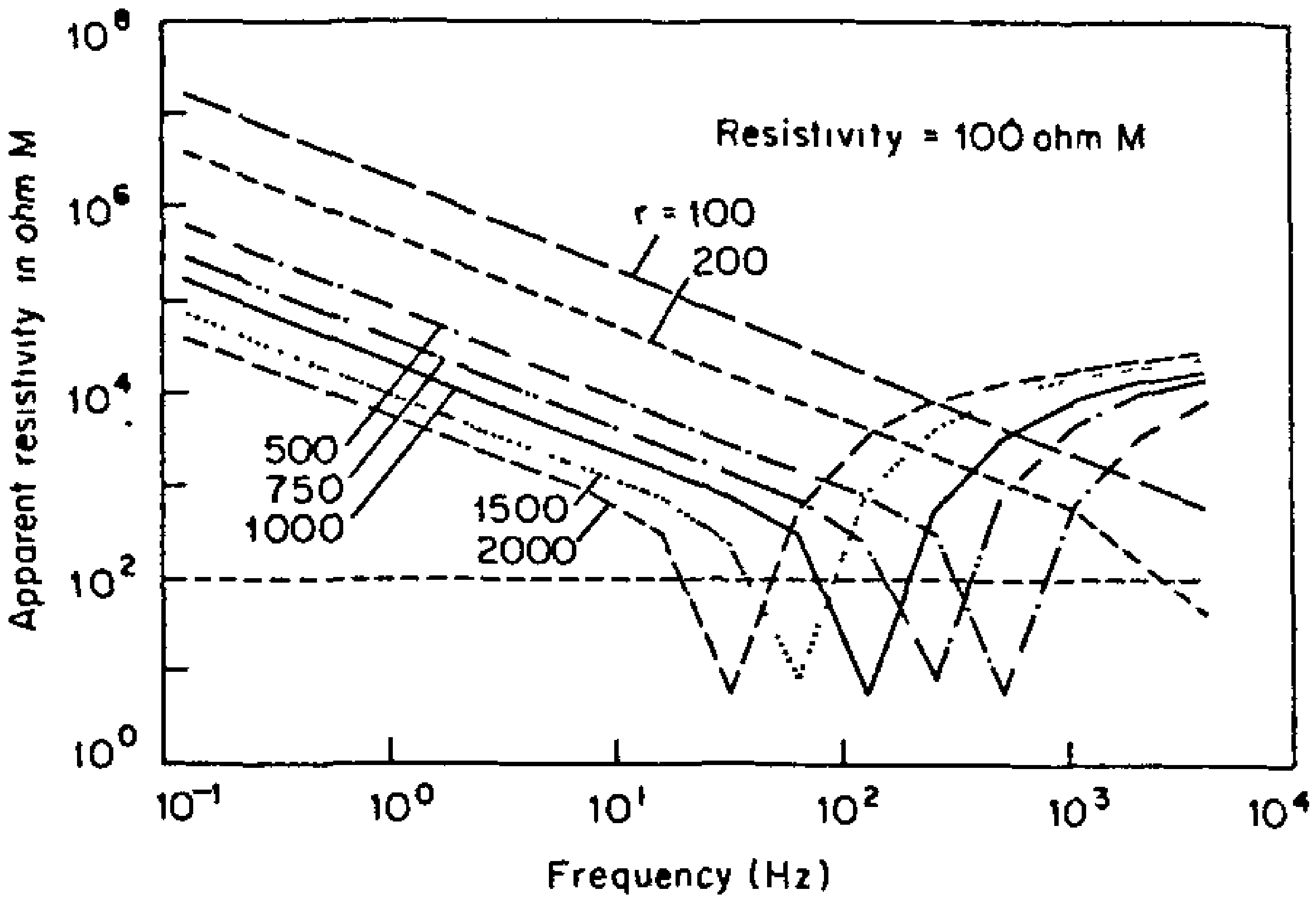

Figure 6. Homogeneous medium CSAMT response (HED source)

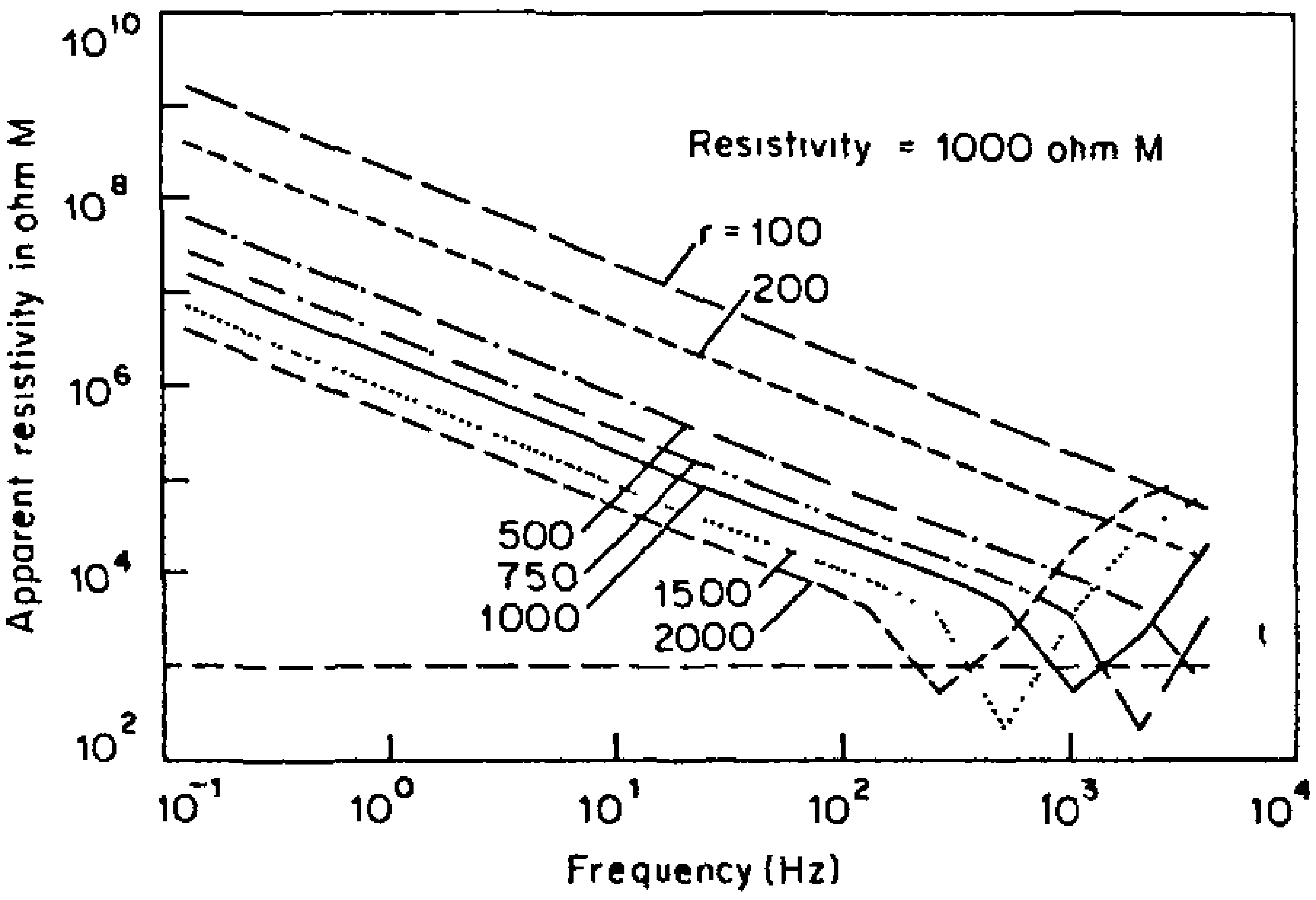

Figure 7. Homogeneous medium CSAMT response (HED source).

Analysis

Critical frequency

The present study is utilized to identify the 'critical frequency', f_c below which the near field solution for VMD and HED source is valid for different combinations of transmitter–receiver separation **r** and conductivity values σ of the homogeneous medium.

Figures 8 and 9 present nomograms indicating f_c.

Near field corrections

In the CSAMT survey, it is ideal to choose the **f** and **r** such that for all frequencies the measurements are made in the far field zone for a given geological situation. However, the distance between the transmitter and receiver locations is constrained in view of decreasing field strengths of different EM field components with

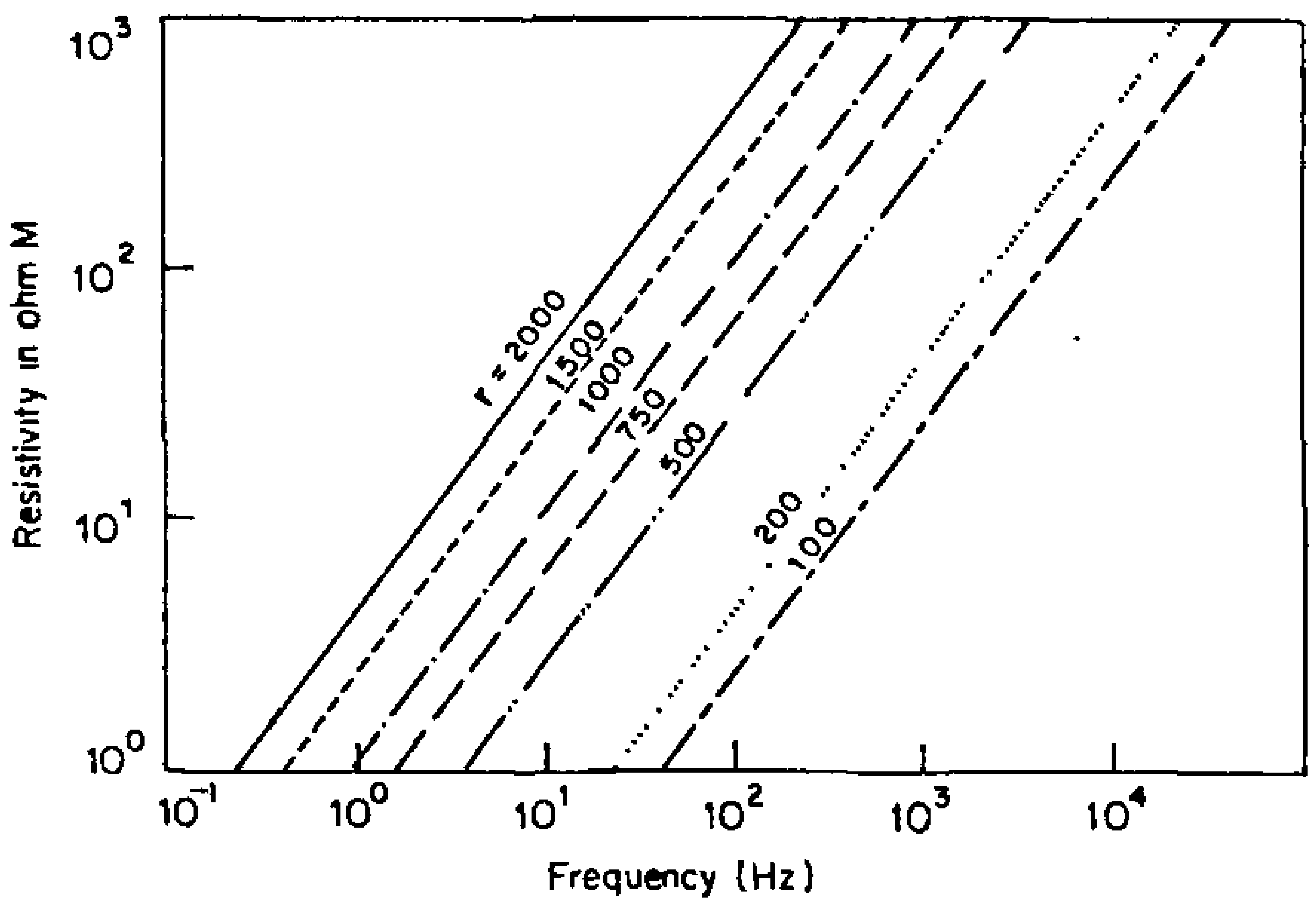

Figure 8. Critical frequency (f_c) for magnetic dipole source

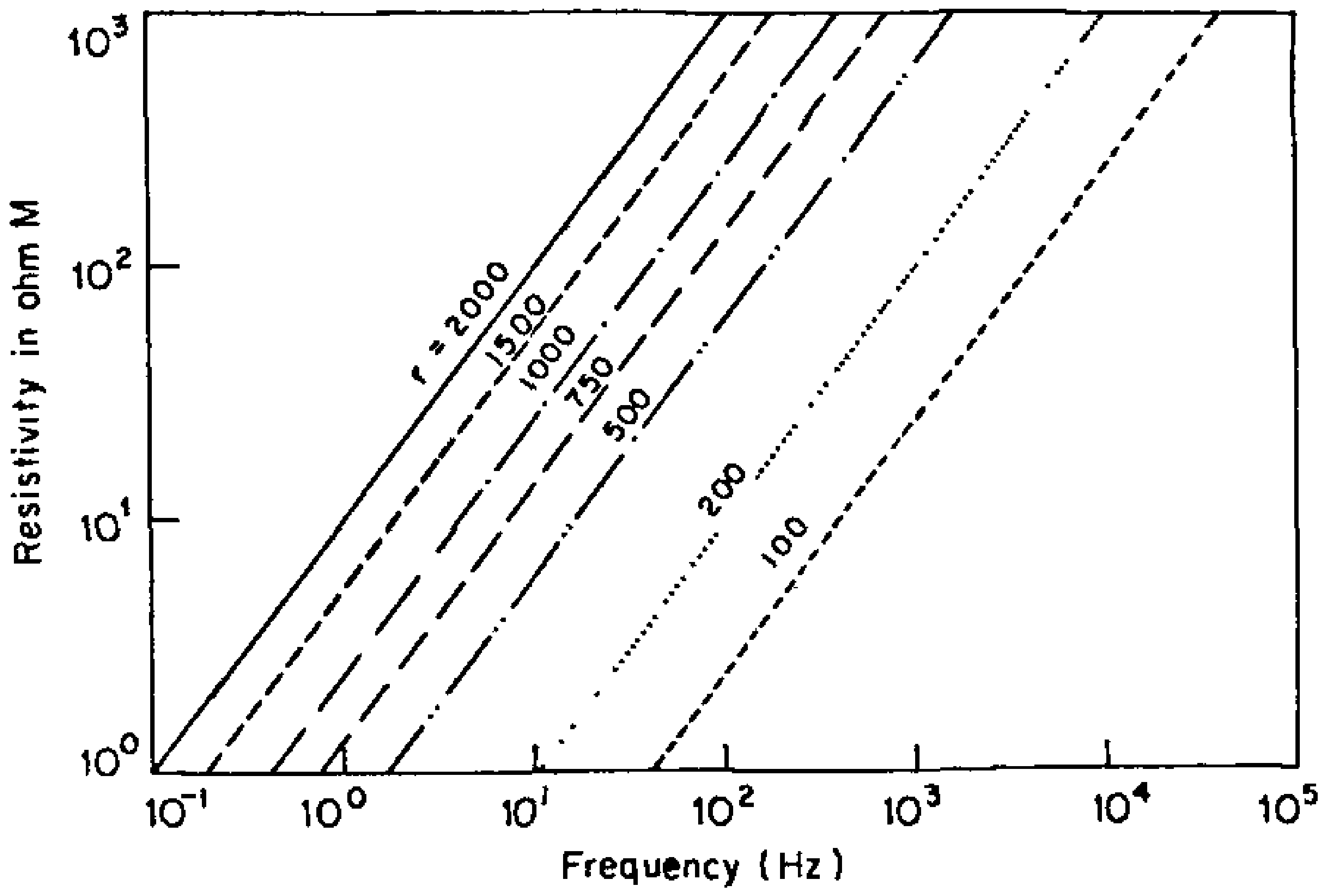

Figure 9. Critical frequency (f_c) for electric dipole source.

Table 1. Computation of corrected resistivity for CSAMT data

Frequency f (Hz)	ρ_{Cag}	$\lvert Z\rvert/fr$	η	Corrected ρ
0 5	4×10^6	0 008	0.00025	1000
1	2×10^6	0.004	0.0005	1000
5	4×10^5	0 0008	0 0025	1000
10	2×10^5	0 0004	0 005	1000

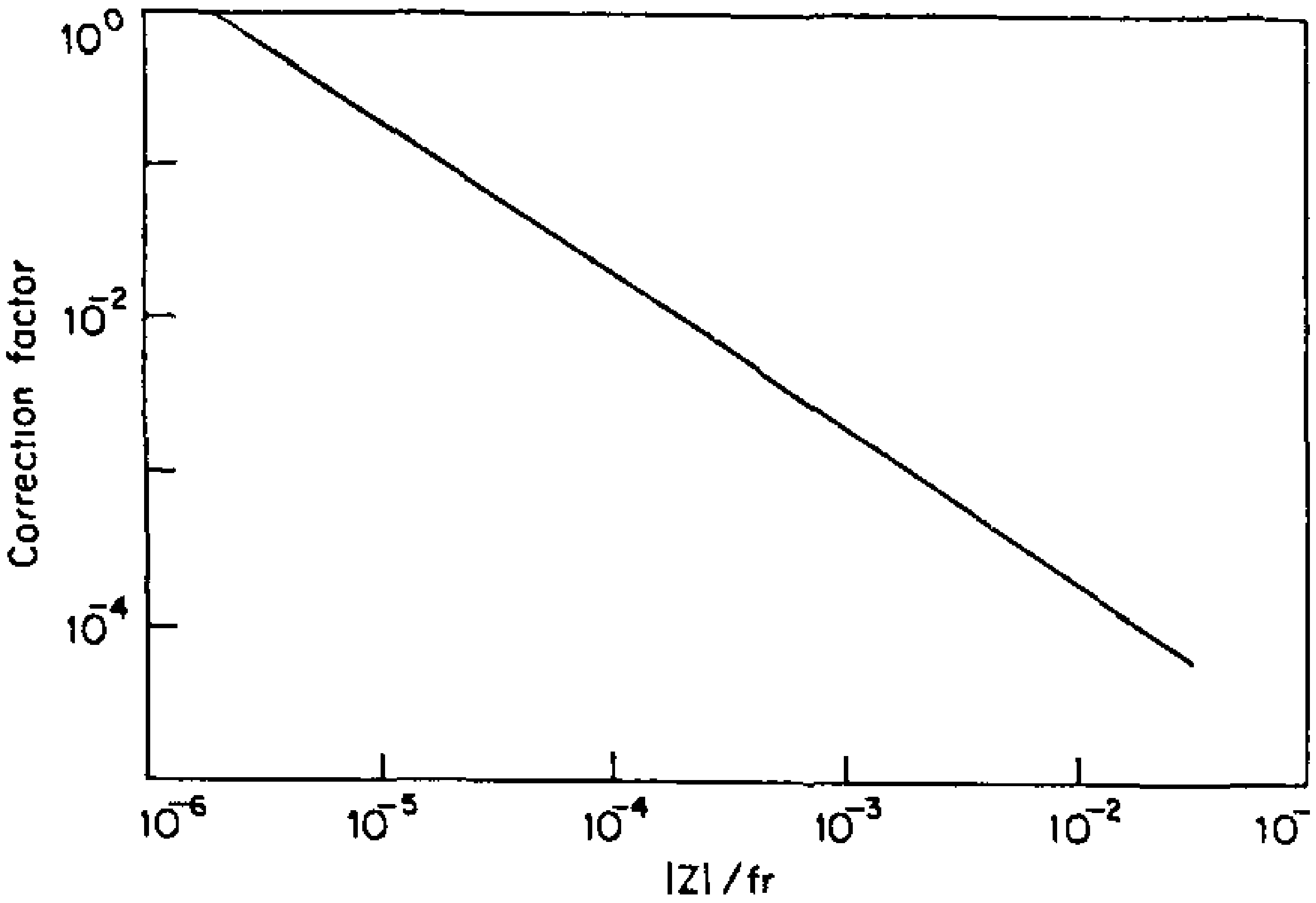

Figure 10. CSAMT near field correction (η) for homogeneous medium

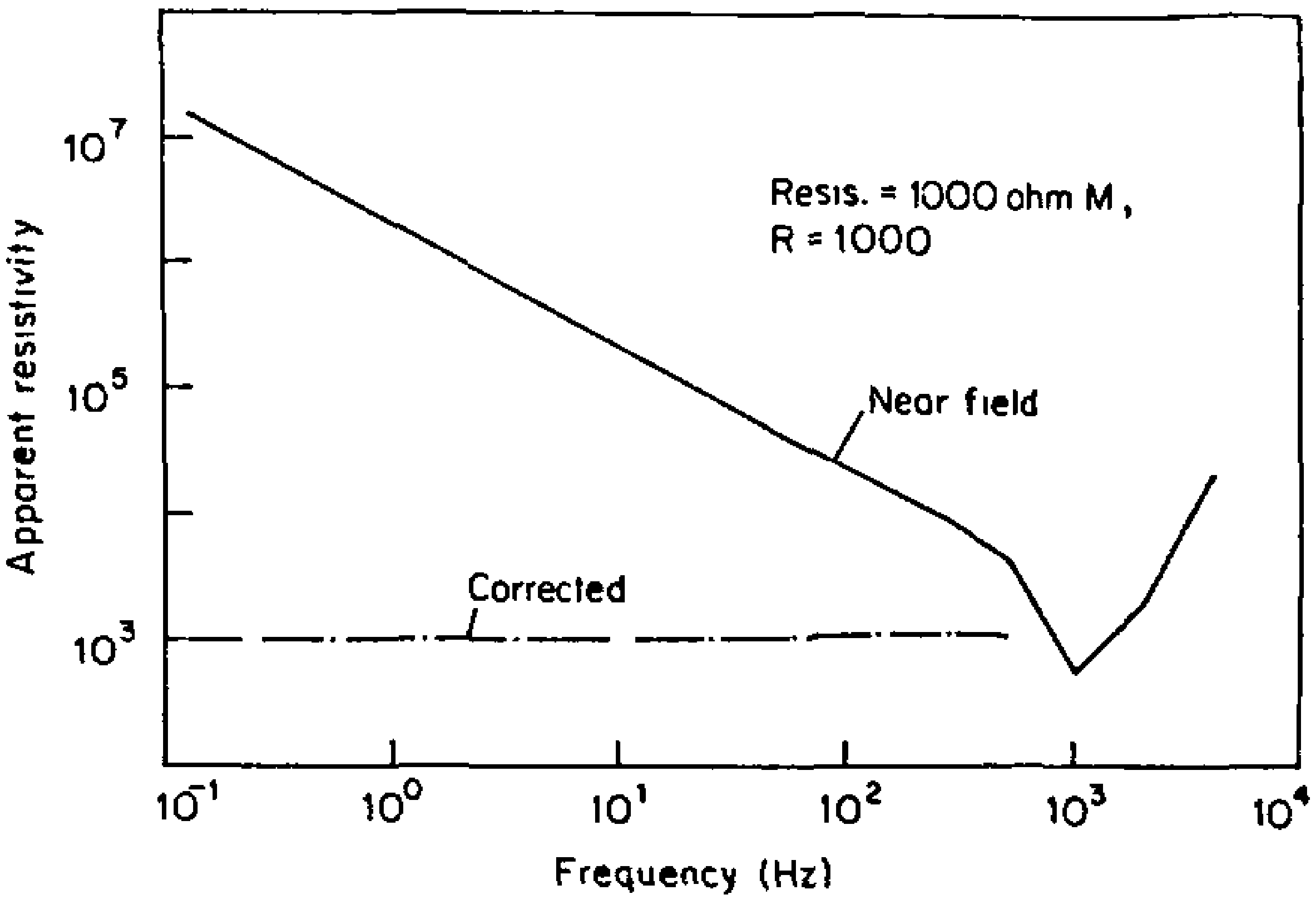

Figure 11. Near field correction (VMD source).

distance (a detailed discussion is provided by Kaufman and Keller[34], Svetov[36], Vanyan[50, 51]). Where the plane wave assumption is valid the field strength may be low and where the signal is strong (near field zone and transition zone $r \approx \delta$, $|kr| \approx 1$) the plane wave assumption may not be valid.

The near field correction curves for broad side position for r = 900 m and dl = 600 m and the frequency range of 1 to 10,000 Hz are produced by Bartel and Jacobson[14]. They have also presented an automated way of correcting the near field data utilizing the computed apparent resistivities based on EMFIN4 computer programme[56] for homogeneous half space with resistivities ρ_1 and ρ_2. The corrected ρ_c can be obtained as[14]

$$\log(\rho_c) = \frac{\log(\rho_m / \rho_{\mathrm{al}}) \cdot (\rho_2 / \rho_1)}{\log(\rho_{\mathrm{an}} / \rho_{\mathrm{al}})} + \log \rho_1 \qquad (40)$$

However, Maurer[57] and Szarkar[58] pointed out that such a correction is model specific and cannot be applied universally. MacInnes[59] describes an iterative technique which takes a far field Cagnaird resistivity as a first guess to obtain the near field corrected apparent resistivity values.

The non-plane wave effects causing the departure of Cagniard resistivity in the near-field zone from the far field solutions can in principle be corrected on the basis of the field behaviour in these zones. The present study is utilized to obtain such a correction as described below.

Introducing a correction factor η such that $\eta = \rho_{far}/\rho_{near}$ we find that η is a function of known quantities of $Z\,(= E_\phi/H_r)$, f and r. η for $\mu = \mu_0 = 4\pi \times 10^{-7}$ is presented in Figure 10.

Table 1 shows the scheme of such a correction for the ρ_{cag} shown in Figure 11. A similar correction factor was suggested by Yamashita and Hallof[4].

The electric and magnetic fields in the near field solutions of electric and magnetic dipoles are independent of frequency and hence the impedance and the sounding data in the near field zone (which of course cannot be avoided in the field sounding data).

Thus the attention is to be diverted to transition zone data which contains more useful information but is complicated in view of the artificial 'undershoots' occurring in these zones.

In conclusion, it may be pointed out that any meaningful understanding of the CSAMT data can be achieved only by considering the full structure of the EM field due to a particular source, once the measurements involve near and transition zones.

Conclusions

The results of the present study have been used to assess the parameters for which the near field conditions are valid.

However, there is a definite need to further investigate the CSAMT response using the general equations without resorting to approximations of the electromagnetic field and develop the CSAMT technique in the country in its totality.

---

1. Goldstein, M. A. and Strangway, D. W., *Geophysics*, 1975, **40**, 669–683.
2. Sandberg, S. K. and Hohmann, G. W., *Geophysics*, 1982, **47**, 100–116
3. Ostrander, A. G., 87th Annual Northwest Mining Association Convention, December 4, Spokane, Wa, 1981.
4. Yamashita, M and Hallof, P. G, Phoenix Geophysics Limited, 55th SEG Annual convention Washington, October 1985.
5. Van Blaricom, R and O'Connor, L. J., Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater (Exploration 1987), Toronto, Ontario, Sep 21–Oct 1, 1987.
6. Lakanen, E, 4th Scientific Assembly of the International Association of Geomagnetism and Aeronomy, 1981.
7. Lakanen, E, *Geophysics*, 1986, **51**, 1628–1646.
8. Hjelt, S E., Heikka, J. V., Lakanen, M. E., Pelkonen, R and Pietila, R., in *Electrical Prospecting for Ore Deposits in the Baltic Shield* (eds. Hjelt, S. E. and Fokin, A. F.), Issue 2, Electromagnetic Methods, Rep. of investigation, Geol. Survey of Finland, 1986.
9. Uchida, T., Yokokawa, K. and Nishikawa, N., Extended Abstracts, 57th Annual International SEG Meeting and Exposition, 1987, pp 217–219.
10. Yokokawa, K, *Geophysical Exploration* (ed. Butsuri Tanko), 1984, vol 37, pp. 279–286
11. Austpac Gold, N. L., Quarterly report to 31st December 1987 (ed. Austpac Gold, N. L), GPO Box 5297, Sydney NSW 2001.
12. Hughes, L. J. and Maas, J. L., Presented at the 49th Meeting of the European Association of Exploration Geophysicists, Belgrade, Yugoslavia, 1987.
13. Yamashita, M, Hallof, P. G. and Pelton, W. H, Expanded abstracts and biographies, 55th Annual International SEG Meeting and Exposition, 1985, pp. 276–278.
14. Bartel, C. and Jacobson, R. D., *Geophysics*, 1987, **52**, 665–677.
15. Hughes, L. J., Carlson, N. R. and Ostrander, A. G., Expanded abstracts and biographies, 54th Annual International SEG Meeting and Exhibition, 1984, pp. 102–104.
16. Hughes, L. J. and Carlson, N. R., *First Break*, 1987, **5**, 403–418.
17. Ostrander, A G, Carlson, N. R. and Zonge, K. L., Expanded abstracts with biographies, 53rd Annual International SEG Meeting, 1983, pp. 60–63
18. Ostrander, A. G., Vugteveen, R. Wm, Hughes, L. J, Carlson, N. R. and Zonge, K. L., Zonge Engineering & Research Organization, Inc., 1984.
19. Fryberger, J. S. and Tinlin, R. M., Proceedings of the 1st National Conference on Abandoned Wells, Problems and Solutions, 1984, pp. 84–117.
20. Syed, T., Zonge, K. L., Figgins, S. J and Anzzolin, A. R., 2nd National Conference and Exposition, Fort Worth, Texas, February 12–14, 1985.
21. Zonge, K. L., Figgins, S. J. and Hughes, L. J., Expanded abstracts and biographies, 55th Annual International SEG Meeting and Exposition, 1985, pp. 147–149.
22. Hughes, L. J, Zonge, K. L. and Carlson, N. R., in *Unconventional Methods in Exploration for Petroleum and Natural Gas* (ed. Davidson, M. J), Southern Methodist University, 1986, pp. 5–26.
23. Tinlin, R. M, Hughes, L. J. and Anzzoln, A. R., in *Field Methods for Ground Water Contamination Studies and their Standardization* (ed. Collins, A. G. and Johnson, A. J.), American Society for Testing and Materials, 1988
24. Bartel, L. C. and Dobecki, T. L., SME-AIME Annual Meeting, Dallas Texas SME Reprint, 1982, pp. 82–97, 1–9.
25. Duff, B M. and Lepper, C. M., Technical papers, 50th Annual International SEG meeting and Exposition, 1980, pp. 3449–3467.
26. Bartel, L. C., Proceedings of the 8th Underground Coal Conversion Symposium, 1982, pp. 59–70.
27. Vozoff, K, *Magnetotelluric Methods*, SEG, Oklahoma, USA, 1986.
28. Nabhigian, N M, *Electromagnetic Methods in Applied Geophysics*, SEG, Oklahoma, USA, 1987, vol. I.
29. Ward, S. H. and Hohmann, G. W., in *E.M. Methods Theory and Practice* (ed. Nabhigian, M N), SEG, USA, 1987, vol. 1, pp 131–311.
30. Wait, J. R, *Can J. Phys*, 1961, **39**, 1017–1028.
31. Wait, J. R., *Electromagnetic Waves* (ed. Langer, R), University of Wisconsin Press, 1962, pp. 243–290.
32. Wait, J. R., *Electromagnetic Waves in Stratified Media*, Pergamon Press, Oxford, 1962.
33. Bannister, P. R., *Radio Science*, 1966, **1**, 1321–1330.
34. Kaufman, A A. and Keller, G. V., *Frequency and Transient Soundings*, Elsevier, Amsterdam, 1983.
35. Wait, J. R., *Can J. Phys.*, 1951, **29**, 577–592.
36. Svetov, Theory methodology and interpretation of low frequency inductive electrical prospecting data (In Russian) Nedra-Moscow, 1973.
37. Khmelevskii, V K. and Bondarenko, V. M (eds) *Electrical Prospecting, Vol I* (Handbook of Geophysics In Russian), Nedra, Moscow, 1989, vol I.
38. Cagniard, L., *Geophysics*, 1953, **18**, 605–635.
39. Bhattacharya, B K, *J. Geophys Res*, 1955, **60**, 279–288.
40. Gupta, J. N, Proceeding of 45th Indian Science Congress Association, Section 3, 1958
41. Wait, J. R., *Geophysics*, 1952, **17**, 378.
42. Slichter, L. B. and Knopoff, L., *Geophysics*, 1959, **24**, 77–78

43 Tikhonov, A N. and Shakhsuvarov, D N, *Izv Akad Nauk USSR*, Ser Geofiz, 1956, **3**

44 Tikhonov, A N and Skugarevskaya, O A, *Izv Akad Nauk USSR*, Ser Geofiz, 1958, **3**,

45 Tikhonov, A. N and Skugarevskaya, O. A, *Izv Akad Nauk USSR*, Ser. Geofiz, 1959, **6**

46. Gasanenko, L. B, *Sci Rep. Leningrad State Univ*, 1959, **278**

47. Gasanenko, L. B and Sholpo, G P, *Problems in Geophysics*, Leningrad University, 1959, pp. 174–183

48. Gasanenko, L B. and Sholpo, G P., in *Problems in Geophysics*, Physical and Geological Series (In Russian), Leningrad Univ Publications, 1960, vol 286, pp 185–232

49. Shienman, S. M and Frantov, G S, in *Geophysical Methods of Prospecting*, VITR, 1958

50 Vanyan, L L., *Prikl. Geofiz*, 1957, **16**

51 Vanyan, L. L., *Prikl Geofiz.*, 1959, **23**

52 Bursian, V. R., *Theory for Electromagnetic Fields in Electrical Exploration*, Leningrad State Univ, 1936.

53. Gray, M, *J Appl Phys*, 1933, **4**

54 Wolf, A, *Geophysics*, 1942, **7**, 414

55. Overholt, K. I, *Geofiz Pros*, 1960, **8**, 470

56 Anderson, W L., US Geol Surv Rept USGS-GD-74-041 205 available from Narl Tech Inf Service as Rept, 1974, PB-238-199

57 Maurer, M, *Geophysics*, 1988, **53**, 725–726

58 Szarkar, A., *Geophysics*, 1988, **53**, 728–729.

59 MacInnes, S C., Ph D Dissertation, University of Arizona, Tucson, Arizona, 1987

ACKNOWLEDGEMENTS We thank DST, New Delhi for financial assistance

Received 21 April 1994; accepted 17 June 1994

MEETINGS/SYMPOSIA/SEMINARS

International Symposium on Weed and Crop Resistance to Herbicides

Place Univ of Cordoba, Spain
Date. 3–6 April 1995

Topics. The symposium will be structured in five sections each covering different aspects of herbicide resistance 1. Herbicide resistant weeds Historical cases, resistance in North America, Australia, Europe and other countries, Newly discovered resistant weeds, Monitoring and testing for resistance. 2 Herbicide resistance mechanisms. Altered target sites; Enhanced metabolism, Other mechanisms. 3. Genetics and biology of herbicide resistant weeds Genetics and heredity of resistance, Population dynamics, Other aspects of the biology of resistant weeds 4 Biotechnological approaches to the development of herbicide resistance in crops, problems and possibilities 5. Managing or avoiding herbicide resistance. Integrated mechanical, chemical and biological methods for weed control

Contact Prof J Jorrin
Departamento de Bioquímica y Biologia Molecular ETS
Ingenieros Agrónomos y Montes
Universidad de Córdoba
14080 CÓRDOBA
Spain
Phone 34 57 218439/34 57 218830
Fax 34 57 218830/34 57 218563
E mail. bfljonoj@lucano uco es

International Conference on Differential Equations – Theory, Methods and Applications

Place Hyderabad, India
Date 20–23 February 1995

Topics include· Ordinary, partial and functional (deterministic and stochastic) differential equations, Integral and integro-differential equations, Control theory, Difference equations, Dynamical systems (continuous and discrete), Ergodic theory and nonlinear waves, Mathematical biology, Neural networks and other aspects of mathematical modelling in physical, biological, engineering sciences and theoretical physics.

Contact Dr B G Sidharth
Director, B M. Birla Science Centre
Adarsh Nagar, Hyderabad 500 463, India
Phone 91 40 235081/598021/241067
Fax. 91 40 222483
E mail deconf@bschyd uunet in

2nd Agricultural Science Congress

Place Hyderabad
Date. 19 – 21 January 1995

The following three symposia will be organized during the Congress 1 National Water Policy, 2 Vector Biology covering research and development aspects of the vectors of diseases of both farm animals and plants, 3 Integrated on-farm and off-farm employment

Contact Dr M V. Rao
Chairman, Organizing Committee
2nd Agricultural Science Congress
Andhra Pradesh Agriculture University
Hyderabad 500 030
Phone 40 245035 (Off), 40 319101 (Res)
Fax 40 245035, Telex 425 6936 APAU IN