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ACKNOWLEDGEMENTS. We thank the Director, NIO, Goa, for interest in the preservation of underwater heritage of India and for the permission to publish the paper. We also thank Prof. A. K. Singhvi, PRL, Ahmedabad for TL dates of potsherds and Dr C. P. Rajendran for obtaining two radiocarbon dates by AMS method from abroad. Thanks are also due to the Director, BSIP, Lucknow for conventional radiocarbon dates. S. B. Chitari, Sham Akerkar and R. Uchil prepared the line drawings. This is NIO contribution No. 4181.

Received 7 March 2005; accepted 16 August 2005

An electromagnetic moving source system for detection of subsurface mineralized zones

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A frequency-domain electromagnetic prospecting moving source device is designed to detect shallow subsurface conductors. Towards this, a microprocessor-based electromagnetic modelling instrument is developed with high degree of accuracy in measurement. The equipment is tested in the laboratory to check its design and performance. In this device, the transmitter and receiver coils are parallel but non-coplanar. The receiver coil is positioned strategically in such a manner that it is not affected by the primary field and senses only the secondary field generated by the conductor. In dipole–dipole set-up, it measures the amplitude of the anomalous field. The operating frequency can be varied from 1 to 30 kHz and separation between the transmitter and receiver coils can be moved from 0.12 to 0.29 m. Measurements can be made to within ± 1% of the free-space field, though absolute accuracy is less. It is found that depth of exploration this moving source system is about 40% more compared to that of a similar conventional moving dipole EM system.

Keywords: Depth of exploration, electromagnetic prospecting, moving source system, subsurface mineralized zones.

IN frequency-domain electromagnetic (EM) exploration, several moving source–receiver systems have been fruitfully used for nearly six decades to detect shallow massive sulphide ore bodies. Depth of exploration for most of the moving source systems is 0.6–0.8 *l* (*l* is the transmitter–receiver separation), as the secondary field produced by a conducting body is quite small in comparison to the strong primary field; accurate measurement of resultant field to primary field ratio is always difficult. To circumvent this problem, time-domain methods were developed where the secondary field is measured during the period when the primary field is switched off.

In this communication, a device is proposed wherein the transmitter (*T*) and receiver (*R*) coils are kept parallel but non-coplanar. In this set-up, one of the parallel components of the time-varying EM field surrounding a circular transmitter coil is zero at certain locations. If the receiver coil is located at these strategic points and parallel to the transmitter, the primary field does not induce currents in the coil. Thus the induced currents are only due to the secondary field from the target. In the absence of the primary field, it can be measured with high accuracy.

The magnetizing forces parallel and perpendicular to the dipole of magnetic moment *m* are given by Parasinnis[1] as:

$$H_{//} = \frac{m(3\cos^2\theta - 1)}{4\pi L^3}, \tag{1}$$

$$H_{\perp} = \frac{3m\sin\theta\cos\theta}{4\pi L^3}, \tag{2}$$

where θ is the angle and L the separation between T and R, as shown in Figure 1.

Equation (1) shows that $H_{\parallel}$ is zero if $\cos\theta = \pm 1/\sqrt{3}$, or $\theta = 54.736°$. In the Cartesian coordinate system, T and R are parallel but displaced by ± 0.7071 *l* (where *l* is the *T–R* separation in coplanar configuration) along the coil axis. In this situation, the separation between T and R is $L = 1.225\ l$. Thus if the R and T are separated laterally by *l* and displaced by ± 0.7071 *l* with reference to the plane of coils then the parallel component of T will not induce any current in R. This property is clearly independent of the magnitude and frequency of the current in the transmitter coil. Further, due to reciprocity, the locations of T and R are interchangeable.

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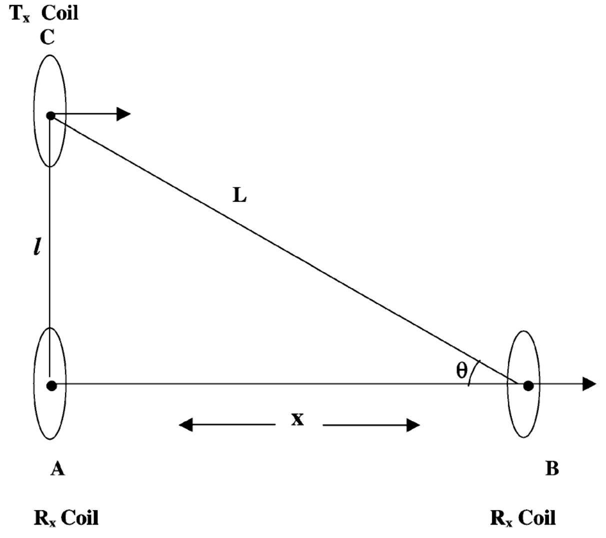
The two coils are placed horizontally and one of the coils should be positioned at least at a height of ± 0.7071 *l*. Therefore, observations cannot be made at heights below 0.7071 *l*. This limitation can be overcome if the coils are placed vertically.

A coincident coil frequency-domain EM system for depth sounding has been described by Duckworth and Krebes[2]. In this method of sounding, the distance from the target is determined by taking the ratio of fields measured at several distances from the conducting target.

In this communication, we propose a device called Vertical Primary Decoupled Coil Configuration (VPDc) as shown in Figure 1. It should be noted that the device measures only the magnitude of the secondary field produced by the target body. In conventional EM system, Vertical Coplanar Coil Configuration (VCc), the total field is measured in comparison to the primary field as in-phase or out-of-phase (quadrature) and expressed as percentage or parts-per-million of the primary field. The anomalous magnitude was measured due to vertical sheet conductor in both VCc and VPDc configurations by physical modelling.

An EM scale model instrument based on 8 bit microcomputer has been designed and developed with the following features:

(a) An 8 bit micro computer with 16 K EPROM, 24 K RAM and 48 I/O lines.
(b) A sinusoidal signal oscillator to generate frequencies in the range 1 to 30 kHz. The output from this has been amplified in a power amplifier before being fed into a transmitter coil to generate the primary field.
(c) The receiver unit consists of high-sensitivity receiver coil with analogue signal processing and receiver amplifier.
(d) A high-speed A/D converter with large dynamic range and a high resolution for digitizing the signals.
(e) A two-line 32 digit alphanumeric LCD to display measured primary and secondary fields.
(f) An RS-232 C-communication link to interface with the PC for transferring profile data. A hard copy of the graphical output of the profile is obtained to analyse experimental results.



Receiver coil displaced through a distance *X* with reference to the plane of the coils from *A* to *B*.

Figure 1. Transmitter and receiver arrangement showing angle θ and L for VPDc configuration.

High accuracy in measurement has been achieved by the enhancement of signal-to-noise ratio through multiple averaging of samples. Detailed system description and operational procedure of the instrument have been described by Nageswara Rao *et al.*[3].

In order to check the performance of the apparatus the following tests and measurements were done.

Inverse cube decay test: The field value decays inversely as the cube of the coil separation in coplanar configuration when a true dipole–dipole system is in free space. This should be indicated in a measurement with varying coil separations as shown in Table 1, satisfying the inverse cube law.

Normalization: Responses provided by frequency-domain system are usually presented in a normalized form that involves dividing the secondary field amplitude by the amplitude of the primary field.

In conventional moving source method, normalization is done with respect to the free space primary field at *R*. This field is logical choice for a reference field. Thus in VCc, normalized anomaly is given as:

$$\text{VCc: } \frac{H^T - H^P}{H^P} \times 100,$$

where H^T and H^P are the total (complex) field components detected when the coil system is near a model and far away from the target respectively.

In the case of the VPDc device, the field at the location of the receiver provides a zero signal parallel to the transmitter, but there exists a field $H_\perp$ perpendicular to it. The amplitude of $H_\perp$ is large and it also has the same order $H_{||}$ of free air response. The secondary field produced by the

Table 1. Decay in primary field with increasing coil separation for vertical coplanar configuration

T–R coil separation *l* (M)	Measured primary field (V)	Calculated primary field (V)
0.14	2.241	2.241
0.15	1.822	1.821
0.16	1.5	1.501
0.18	1.054	1.053

conductor will be feeble (few mV) for $h/L > 1.0$. Hence 10% of $H_\perp$ has been selected for the normalization factor to have relatively large response.

$$\text{VPDc: } \frac{H^S}{H_\perp} \times 100 \times 10,$$

where H^S is the secondary field produced due to the target and $H_\perp$ is the perpendicular component of the primary field.

Responses over a vertical graphite sheet of dimension 0.75 × 0.40 × 0.005 m were taken at a frequency of 5.6 kHz for VCc, and for VPDc at h/l, $h/L = 0.6$ respectively. The measured values were normalized and are shown in Tables 2 and 3 for VCc and VPDc respectively.

Scale test: If the apparatus measures correctly, it should produce identical results for two configurations which are electromagnetically similar. This constitutes a necessary test, since it is the basis of small-scale modelling. To establish this, the following experiment was devised.

A model experiment has been performed in VCc over a half-plane model in resistive surrounding. The *T–R* separation l and operating frequency are selected as 0.15 m and 8 kHz respectively. A graphite sheet 0.75 × 0.40 × 0.05 m is simulated in the half-plane model. H^T data have been acquired by moving the *T–R* coil system across the conductor for $h/l = 0.6$ and 0.8. The same experiment was repeated for another set of $l = 0.12$ m and frequency = 10 kHz for at $h/l = 0.6$ and $h/l = 0.8$. It has been observed that peak amplitude response is the same for the two selected values of l keeping h/l ratio the same. The same model experiment is conducted in VPDc with $L = 0.1714$ m and frequency = 8 kHz, and another set of $L = 0.147$ m and frequency = 10 kHz for $h/L = 0.6$ and $h/L = 0.8$. The secondary field $H_{//}$ is measured across the model by moving the *T–R* coil system. Here also the peak amplitude response is same for the two selected values of L, keeping h/L ratio the same. This satisfies the scale test.

Table 2. Normalized value for VCc

Primary field (V)	Peak response over vertical sheet (V)	Normalized value (%)
0.750	0.7739	3.18
1.500	1.5485	3.22
3.000	3.095	3.17

Table 3. Normalized value for VPDc

10% $H^\perp \times 10^{-3}$ V	Peak response over vertical sheet $\times 10^{-3}$ V	Normalized value (%)
576	10.27	17.83
113	20.97	18.23
230	42.12	18.30

The vertical *T* and *R* coils are attached to a vertical rod so that the height can be varied. The coil holders are mounted on a trolley, which moves on horizontal rails. The target model is a graphite sheet, M1 having dimension 0.75 × 0.40 × 0.005 m and conductivity, $\sigma = 12 \times 10^4$ Sm^{-1}. It is held vertically by a suitable holder and perpendicular to the traverse of the *T–R* system (Figure 2). The coil traverses were positioned to cross the conductor over the middle point of its strike. The height of the *T–R* coil above the top edge of the model sheet is h and the coil separation (l or L) is selected depending upon the configuration VCc and VPDc respectively. *T–R* separations are taken from $l = 0.12$, 0.14, 0.15, 0.16 and 0.18 m for VCc and $L = 0.147$, 0.1714, 0.1837, 0.1959 and 0.2204 m for VPDc. For the present exploratory experiment, the response of vertical planar conductor in resistive host has been studied for varying values of h/l and h/L. Responses over the target were taken for $h/l = 0.4$ to 0.8 and $l = 0.12$ m in VCc and for $h/L = 0.4$ to 1.2 and $L = 0.147$ m in VPDc. The operating frequency is fixed at 5.6 kHz. The anomaly at various positions of the *T–R* coil system could be accurately determined with the help of a scale attached to the rails.

Characteristic VCc amplitude response profiles over the target are shown in Figure 3 for different h/l, $l = 0.12$ m. The response increased as the *T–R* system moved toward the target. Maximum was observed when the *T–R* system was on the top of the target. Amplitude decreases to zero as the *T–R* system crosses the target. The distance between the two zeros is equal to 2.5 l. The amplitude response is less than 0.8% for $h/l = 1.0$ whereas accuracy of the instrument is 1%. In this configuration depth of investigation is equal to 0.096 m ($h/l = 0.8$, $l = 0.12$ m).

Figure 4 shows VPDc amplitude response profiles over the targets for different h/L, $L = 0.147$ m. On either side of the peak, we get zero value. The distance between the two zeros increases with depth to the top of the target. A

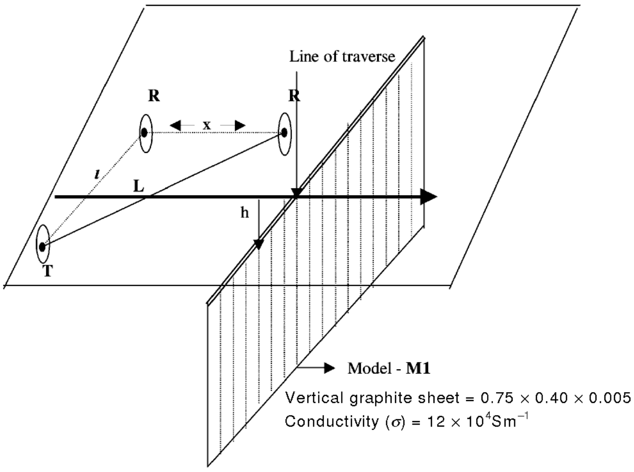


Figure 2. Experimental setup for VPDc configuration.

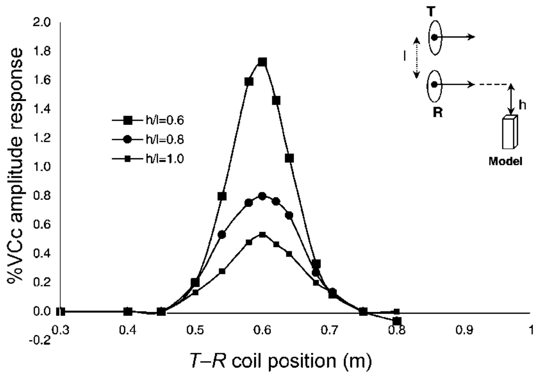


Figure 3. VCc response over vertical graphite model M1 for h/l = 0.6, 0.8 and 1.0; l = 0.12 m.

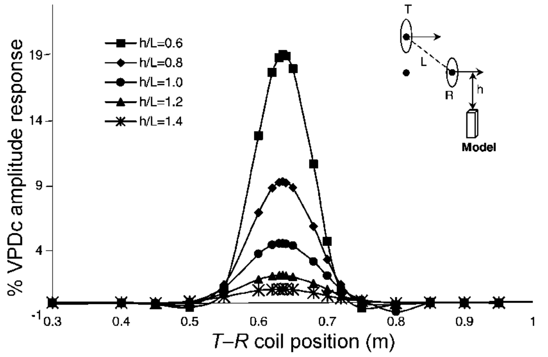


Figure 4. VPDc response over vertical graphite model M1 for h/L = 0.6, 0.8, 1.0, 1.2 and 1.4; L = 0.147 m.

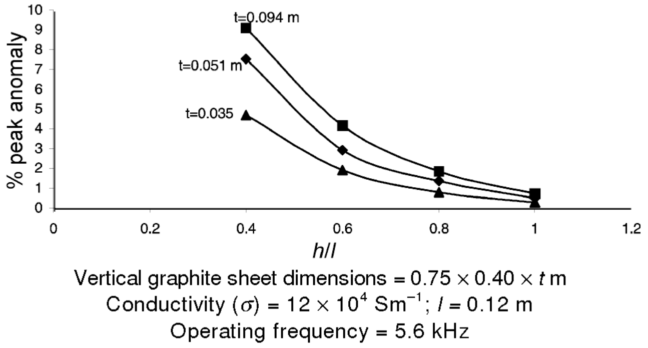


Figure 5. Measure peak amplitude response with varying h/l for different conductances in VCc, l = 0.12 m.

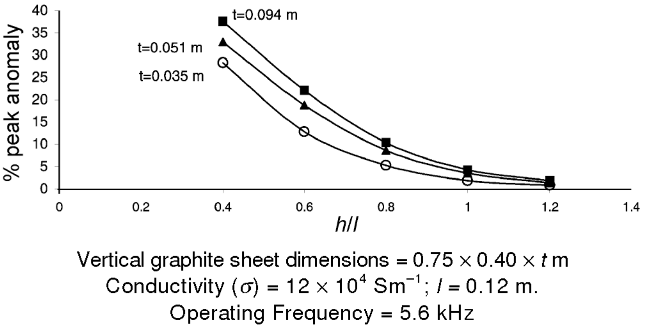


Figure 6. Measured peak amplitude response with varying h/L for different conductances in VPDc, L = 0.147 m.

noticeable response of 1.04% is observed for h/L = 1.4. The depth of exploration for the proposed system can be safely said to be 1.2 L. In this case the depth of investigation is equal to 0.19 m, i.e. the depth of exploration of the our system is equal to 0.19 m.

VCc and VPDc peak amplitude responses over graphite sheets of varying thickness of 0.00315, 0.005 and 0.10 m have been plotted with varying h/L in Figures 5 and 6 respectively. The strike length and depth extents of the three models are 0.75 × 0.40 m respectively. All the models chosen are thin[4]. Peak amplitude increases with increasing conductance for both VCc and VPDC configurations.

The novelty of the present device lies in that the transmitter and the receiver are parallel and coupling between them is zero. The response of VPDc is significantly stronger than that obtained using the conventional VCc system. For a target located at a depth h/L = 0.4, the VPDc device unambiguously yields a response which is at least larger by a factor of 8 compared to the existing VCc device. Thus, the new device is inherently superior to all conventional exploration devices.

In amplitude measurements the cable connection between T and R is not required, which makes the system more convenient to use on ground as well as airborne field surveys. The accuracy of parallel coil positioning and T–R separation can be easily achieved through GPS up to 0.001 m. Development of an instrument measuring in-phase and out-of-phase components employing GPS and radio synchronization is in progress. It may be mentioned here that such a device with phase measurements will be worthwhile, especially to locate deep-seated conductors. Further, a field device needs to be developed and tested for amplitude measurement for the VPDc system.

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ACKNOWLEDGEMENTS. We thank Dr V. P. Dimri, Director, NGRI, Hyderabad for providing the facilities and stimulus to carry out this study and for permission to publish this paper. We also thank Dr S. K. Verma, NGRI for valuable suggestions to improve the manuscript and M. S. Sarma for his assistance.

Received 5 April 2006; revised accepted 4 August 2006