Short Note

VLFPROS—A Matlab code for processing of VLF-EM data

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1. Introduction

The very low frequency electromagnetic (VLF-EM) technique is well established for rapid geological mapping and detection of buried conductive targets. The technique makes use of signal radiation from military navigation radio transmitters. There are about 42 global ground military communication transmitters1 operating in VLF frequency in the range of 15–30 kHz. These stations, located around the world, generate signals which are effectively used for a variety of applications including navigation and communication, ground water detection or contamination, soil engineering, cultural detection, ionospheric, meteorological, archeological, nuclear waste detection and VLF band transmission studies, besides mineral exploration, mapping of fault zones, etc. (Wright, 1988; Philips and Richards, 1975; Sundararajan et al., 2006).

The detection of subsurface conductors is made feasible by means of a portable VLF receiver, which, in most commercial instruments, provides a measure of the inphase and quadrature components of the vertical secondary magnetic fields relative to the horizontal and primary field. Although both inphase and quadrature components contain valuable diagnostic information about the subsurface targets, only a few schemes exist for extracting the required information and thereby relating the observed anomalies to their causative sources. One such a scheme first proposed by Fraser (1969) is a simple filtering technique known as Fraser filtering. The technique is analogous to passing the inphase data through a band pass filter which (i) completely removes DC bias and greatly attenuates long wavelength signals; (ii) completely removes Nyquist frequency related noise; (iii) phase shifts all frequencies by $90^\circ$; and (iv) has the band pass centered at a wavelength of five times the station spacing. Fraser filtering converts somewhat noisy, non-contourable inphase components to less noisy, contourable data which ensures greatly the utility of VLF-EM survey. VLF-EM contour maps form a meaningful complement to magnetic maps.

Yet another filtering proposed by Karous and Hjelt (1977, 1983), enables the geophysicist to generate an apparent current density pseudosection by filtering the inphase data and which provides a pictorial indication of the depth of the various current concentrations and hence the spatial disposition of subsurface geological features such as mineral veins, faults, shear zones and stratigraphic
conductors (Ogilvy and Lee, 1991). The finite Hjelt filter method is a more generalized and rigorous form of the widely known Fraser filter (Fraser, 1969), however is derived directly from the concept of magnetic fields associated with the current flow in the subsurface. Application of either Fraser or Hjelt filter or both to VLF inphase component enables one to obtain the equivalent current densities at a constant depth which would cause a magnetic field. In the absence of numerical modeling, Fraser and Hjelt filtering techniques are proved to be effective as they provide a simple scheme for semi-quantitative interpretation.

The aim of this work is to present a simple and elegant code with GUI-based MATLAB functions for processing and interpretation of VLF-EM data. The utility of this program includes: (i) plotting of VLF-EM anomalies as stacked profiles using a user defined filter; (ii) contouring and imaging of the filtered data for understanding the spatial distribution of EM conductors; and (iii) preparation of pseudodepth section of a chosen traverse using Fraser and Hjelt filters. Stacking of profiles, contouring and imaging of magnetic data can be carried out by this code. These features are illustrated graphically over a set of inphase component of VLF-EM besides contours of magnetic signal, over a mineralized fracture zone from Chhattisgarh, India (Ramesh Babu et al., 2004).

2. Filtering of VLF-EM data

Modern commercial VLF-EM instruments read directly the inphase and quadrature components in digital form of the vertical secondary magnetic field expressed as percentage of the primary horizontal magnetic field. VLF inphase data often yield complex patterns which require a considerable study for proper interpretation of the profiles. The most popular form of presenting 2-D VLF-EM data over a given area is in the form of stacked profiles. These are profiles along each survey line plotted on a 2-D plane in the same relative position as the lines. VLFPROS facilitates plotting the data in the form of stacked profiles, which in turn demarcates spatial location of conductors.

Linear filtering technique developed by Fraser (1969) transforms non-contourable inphase data to contourable form. Inphase component (VIP) exhibits crossovers in the presence of a conductor/conducting zones (McNeill and Labson, 1991) as shown in Fig. 1(a). The filtering process simply involves running a four-point weighted average using the weights of $-1, -1, +1, +1$. This simple digital filter operator passes over the inphase component as shown in Fig. 1(b).

Fraser filtered inphase component when plotted generally peaks over the top of the conductor as shown in dotted line (Fig. 1(a)). This alteration of the raw data is termed as Fraser filtering and can be summarized in two statements: (i) the filter phase shifts all spatial frequencies by 90°, i.e., it turns crossovers into peaks or troughs; and (ii) it exhibits a band pass response, in other words, it greatly diminishes either sharp irregular responses (noise) or long rolling responses. At the same time, it accentuates responses which are the nearest to the filter’s shape. Subsequently, the filtered output is plotted again at the center of the filter shown (Fig. 1(b)) as Fraser filter coefficients. The filter is then moved ahead of one data spacing and the procedure is repeated. Once all the profiles are filtered, the filtered output is contoured and imaged. The interpretation of maps/images generated from the Fraser filtered output is qualitative in nature. A large amplitude can be considered as a large conducting zone. Very sharp and low amplitudes indicate shallow sources, and, conversely, broader amplitudes of large wavelengths indicate progressively deeper sources.

The Hjelt filter technique is a more generalized and rigorous form of the Fraser filter but is directly derived from the concept of magnetic fields associated with current flow in the earth. From the filtered VLF inphase component, one obtains the equivalent current densities at a constant depth which would cause a magnetic field. That is, the filter attempts to determine the current distribution responsible for producing the measured magnetic field. Determination of the filter shape (coefficients) is fairly a simple mathematical process (Karous and Hjelt, 1977). A number of filters with various lengths and shapes can be developed, however the optimized Hjelt filter (Karous and Hjelt, 1983) can be expressed as

$$\frac{AZ}{2I_a(0)} = 0.205 H_{-3} - 0.323 H_{-2} + 1.446 H_{-1}$$

$$-1.446 H_1 + 0.323 H_2 - 0.205 H_3,$$

where $I_a(0) = 0.5 \left[ I(\Delta X/2) + I(-\Delta X/2) \right]$ and where $H_{-3}, H_{-2}, \text{etc.}$ are the measured data at six consecutive stations, $\Delta X$ is the measurement interval and $I_a$ is the apparent current density. Procedures for applying the Hjelt filter is exactly the same.
as that of Fraser filter, including proper orientation so as to match expected anomaly shapes. While the filter passes along the data profile, the inphase components are multiplied by the filter coefficients and then all the six products are added to produce one output value which is represented at the center.

Fig. 1. (a) Schematic sketch of conductor response. (b) Schematic sketch of Fraser filter coefficients. (c) Schematic sketch of Hjelt filter coefficients.
of the filter as shown in Fig. 1(c). The process continues till the end for all the profiles. Then the output is contoured and interpreted in a similar way to that of the Fraser filter.

3. Pseudosection

An additional interpretative tool is based on pseudosection of the filtered outputs. This is obtained by processing a chosen single data profile either by Fraser or Hjelt or both at various lengths or spans. As the length of the filter increases, responses from increasing depths are successively emphasized. Therefore if the outputs are arranged on a section such that greater depths correspond to longer filters than the section should approximately resemble the current pattern in the ground. However, it must be emphasized that this is only an approximation to the section (Wright, 1988; Fraser, 1981). Thus, construction of the pseudosection consists of a number of steps like processing the profiles with as many as number of levels (approximately 5 or 6), at each level, in terms of integer multiples of the station spacing \((n\Delta x)\) where \(n\) is the number of levels and \(\Delta x\) is the station spacing. Finally, plotting the results separated by \(n\Delta x\) at each level one below the other so as to form a section. Interpretation of the pseudosection is also fairly general and consists of the following sequences: (i) areas with high current-densities correspond to good conductors; (ii) negative contours are due to high resistivities; and (iii) the trend of the contour pattern indicates the dip of the conductor.

4. Matlab implementation

VLFPROS is a Matlab Version 6.0 R12-based program for processing of VLF-EM data and which can also be implemented on Version 7.0 R14. This program can be activated either by an ‘m’ file

![Flow chart of VLFPROS.](image-url)
“VLFPROS” or by a figure file of “VLFPROS” as found in flowchart (Fig. 2). From Matlab command window, once the VLFPROS is loaded on activation, a window consisting of push buttons with various options such as (i) contouring, (ii) stacked profiles and (iii) pseudosection display on the screen. The VLF inphase component which is the input to VLFPROS has to be created in three different columns separated by a comma or space and free from headers. The first column should contain X location, second column Y location and the third column should contain the inphase component of VLF-EM data. Example ‘vlfip.dat’ is a VLF inphase component data which is available for demo (Fig. 3).

To begin with stacked profiles option is selected and which displays filtering and stacked profiles window. This window enables plotting of raw data, filtering (with various options like Fraser, Hjelt_1, Hjelt_2) and plotting of filtered outputs in the form of stacked profiles. The input data file has to be specified in the appropriate dialog box enter file name option and then click plot profile for raw data stacked profiles. Further, one of the three available filters can be made use of to filter the input data by entering the appropriate filter name (Fraser.txt/Hjelt_1.txt/Hjelt_2.txt). Then specify an output file name against enter output file name dialog box and then enter to obtain the stacked profiles of the filtered data. To contour/image of the filtered output, go to VLFPROS and click contouring. Contouring and imaging window appears on the screen. Contouring and imaging can be realized by specifying a data file name in the appropriate dialog box, the maximum and minimum value of the input data file appear. An appropriate cell size has to be specified. Select a gridding method out of available options linear, cubic, nearest, V4 (Matlab 4 griddata method) from the popup menu, which results the interpolated minimum and maximum contour values. The cubic and V4 methods produce smooth surfaces while ‘linear’ and ‘nearest’ have discontinuities in the first and zeroth derivatives respectively (Sandwell, 1987). Finally specify the appropriate contour interval for contouring.

To prepare pseudosection, activate VLFPROS and click pseudosection which displays the pseudosection window. Enter the input file name of raw data and select a specific profile line number which is to be pseudosectioned. Once the line number is selected from the popup menu, enter the appropriate filter and output files in their respective dialog boxes. Then choose the number of levels from popup menu and then click to write the filtered output to a file which can further be used for obtaining the pseudosection using contouring option.

The entire operations are illustrated with VLF inphase component (vlfip.dat) pertaining to mineralized fracture zone from Chhattisgarh, India. The stacked profiles of raw data and its image are shown in Fig. 4(a) and (b), respectively. While the Fraser and Hjelt filtered outputs in the form of stacked profiles are given in Fig. 5(a) and (b), and the corresponding images are given in Fig. 6(a) and (b), respectively. The pseudosections of the chosen line (traverse 50) based on Fraser and Hjelt filters are shown in Fig. 7(a) and (b). The magnetic data from
Fig. 4. (a) Stacked profiles of VLF-EM inphase component. (b) Image with contours of VLF-EM inphase component.

Fig. 5. (a) Stacked profiles of Fraser filtered VLF-EM inphase component. (b) Stacked profiles of Hjelt filtered VLF-EM inphase component.
Fig. 6. (a) Image with contours of Fraser filtered VLF-EM inphase component. (b) Image with contours of Hjelt filtered VLF-EM inphase component.

Fig. 7. (a) Pseudodepth section of Fraser filtered VLF-EM inphase component. (b) Pseudodepth section of Hjelt filtered VLF-EM inphase component.
the same location is imaged and shown in Fig. 8 and which may be compared with the Fraser and Hjelt images (Fig. 6(a) and (b)) of the VLF-EM inphase component.

5. Conclusion

The VLFPROS, thus a simple Matlab code with GUI which produces stacked profiles of both raw and filtered data, in addition to their images with contours. This code can also be used for processing of magnetic data to obtain the contours/images/stacked profiles. This code can be modified for additional features. Further, pseudosections provide first hand information regarding the number, size, depth and relative disposition of the conductors.

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Appendix A. Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2006.02.021.

References