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論文題目	Development and application of methods to evaluate temporal changes in subsurface resistivity structures using magnetotellurics （地磁気地電流法を用いた地下比抵抗構造の時間的変動評価手法の開発と応用）		

（論文内容の要旨）

Time-lapse magnetotelluric (MT) exploration has been conducted for a detailed discussion on temporal changes in subsurface resistivity structures, especially around geothermal areas. However, two challenging subjects remain: cultural noise effects and source-dependent bias stemming from spatially-heterogeneous source currents. Cultural noise mixed in observed electromagnetic (EM) data can yield large estimated errors of MT responses, which result in failure to detect time-varying impedances. Then this study supposes establishment of the plane-wave assumption, in which incident EM fields are horizontally uniform and geomagnetic temporal variations have no spatial gradient. If this assumption is not satisfied, MT responses are biased and shift from their true values.

This study presents a theory describing the bias within MT responses arising from localized source currents. Subsequently, an improved algorithm of Frequency-Domain Independent Component Analysis for processing noisy MT data (FDICA-MT) was proposed for removing the noise effects. For excluding the source-dependent bias within impedances, a technique to assess spatial gradients of geomagnetic temporal variations from several geomagnetic spectrograms using Multi-Channel Nonnegative Matrix Factorization (MC-NMF) was developed. By applying these methods to the EM data acquired at the Kakioka magnetic observatory, the temporal variations in MT responses owing to changes in the subsurface resistivity structure were well detected.

The background, purposes, and structure of this study, reviews of related preceding studies, and unsolved essential problems that motivated this study are introduced in Chapter 1.

Chapter 2 formulates equations of EM fields by supposing localized source currents. On the basis of these equations, Chapter 3 calculates MT responses by changing the vertical and horizontal distances between an observation site and the source current. Consequently, MT responses shift from the true values and vary dependent on the distances. Because these distances change temporally, for an exact interpretation of time-varying MT impedances, check of the condition of ionospheric currents is indispensable. Furthermore, the mathematical underpinnings for the source-dependent bias and the plane-wave assumption were noted.

Chapter 4 presents FDICA-MT, which was designed to separate noise directly from observed data. For checking the noise-reduction performance, FDICA-MT was applied to the EM data acquired at Kakioka. The results revealed that the MT responses derived by FDICA-MT were smoother and have smaller error than those by a conventional method. The robustness of the noise-reduction performance of FDICA-MT was tested quantitatively by analyzing the EM data including synthetic noise components. Although the conventional technique breaks down when more than half of the time-series data are contaminated, FDICA-MT was able to estimate MT responses correctly and with small estimated errors. Furthermore, the proposed method was applied to the EM data acquired in the Chugoku district and at the outer rise

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region off Japan Trench. FDICA-MT yielded higher quality impedances even from real noisy data than the conventional tool.

Chapter 5 presents MC-NMF, which can assess anomalous geomagnetic events that have different spatial gradients from others. The method can work at the time–frequency domain, in which information regarding the geomagnetic temporal variations is included roughly as much as in the time-series data. This study clarified that such anomalous events caused shifts in inter-station transfer functions (IS-TFs) between the geomagnetic data acquired at the Kakioka and Memambetsu magnetic observatories. Subsequently, the year-to-year changes in IS-TFs between Kakioka and Kanoya, Kakioka and Memambetsu, and Kanoya and Memambetsu were calculated. Although the polarity should be opposite, some IS-TFs exhibit the same polarity as those derived by swapping the output and input data. The results from MC-NMF, numerical examples, and the mathematical proof indicated that the spatial gradients of geomagnetic temporal variations cannot always be assessed on the basis of the IS-TFs if anomalous geomagnetic events are mixed in the geomagnetic data. However, MC-NMF was able to evaluate the anomalous events. Hence, by using IS-TFs with MC-NMF, the spatial gradients of geomagnetic fields can be correctly calculated.

Chapter 6 analyses time-varying impedances from the EM data acquired at Kakioka during 2000–2004. FDICA-MT was employed for removing the noise effects on the MT responses. The interpretation from Chapter 3 and the method of MC-NMF presented by Chapter 5 were used for excluding the impedances affected by the source-dependent bias. Although the MT responses became stable by removing these adverse effects, the temporal variations appeared only in the amplitudes. Because of the synchronized changes throughout the frequencies, they can be considered to result from the temporal variations caused by the static shift. The MT responses shifted widely owing to an increase in the precipitation at Kakioka. On the basis of the geological structures at Kakioka, the rainfall may cause the local resistivity heterogeneities, which are probably the origins of the static shift. Additionally, numerical simulations showed that a 10% decrease in the near-surface resistivity yields the upward and downward shifting in the amplitudes of MT impedances, which corresponded to the observed variations. Such a decrease due to the rainwater incursion is plausible and accordingly, the time-varying amplitudes of the impedances can be considered to reflect the temporal changes in local heterogeneities stemming from precipitation. Therefore, this study succeeded in extracting time-shifting MT responses that result from the temporal variations in the subsurface electrical environment at Kakioka. Furthermore, because of suppressing the noise effects and source-dependent bias, the detected changes have small temporal-scales. By applying the scheme employed in this study, time-varying MT impedances can be exactly detected, which indicates that MT is effective for monitoring subsurface resistivity structures.

Chapter 7 summarizes the concluding remarks, contributions of this study to the field of natural resource engineering, and future works that can be expected to be yielded by applying the techniques, results, and interpretations of this study.

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（論文審査の結果の要旨）

地磁気地電流法(MT 法)は電磁探査法の一種であり，地下深部までの比抵抗構造を計測できるという特長をもち，石油や地熱資源探査のみでなく，地熱貯留層の温度変化や地震の発生に伴う比抵抗構造の時間的変化の抽出などにも応用されている。しかしながら，①電磁ノイズが観測データに混入した場合，電磁場(MT)応答関数の推定誤差が大きくなる問題，および②電離層電流の局在化によって，MT 法で仮定する磁場変動の空間的一様性が満足されないことが知られている。特に②の状況下では，電離層電流の流れる場所に依存して MT 応答関数は変化するために，地下比抵抗の短期的な時間的変化を正確に抽出することはこれまで困難であった。本研究はこれを可能にするために，①と②の問題の解決に資する手法を開発し，長期間の観測データに適用することでその有用性を実証した。主な研究成果は次の 4 点にまとめられる。

(1)電流源と観測点の距離を変化させ，磁場の空間勾配と MT 応答関数との関係を理論的に求めることで，局在化する電離層電流が平面波近似の成立の可否に及ぼす影響を明らかにした。

(2)周波数領域独立成分分析を用いて観測データから電磁ノイズを除去する手法を新たに開発し，気象庁柿岡地磁気観測所の電磁場データに適用したところ，従来法で 11 年間のデータから導出した MT 応答関数と同等の精度を，44 日間分から得ることに成功した。本手法を中国地方で測定された電磁ノイズを含む実データにも適用した結果，従来法よりも高い精度で MT 応答関数を求めることができた。

(3)従来，磁場変動の空間勾配評価には，地上の地磁気観測所間の水平磁場変換関数(IS-TFs)が用いられてきたが，その評価は IS-TFs のみでは困難なことを理論的に示し，実データ解析からも実証した。また，多チャンネル非負値行列因子分析を用いて地磁気データのスペクトログラムから磁場変動の空間勾配を抽出する手法を開発し，これと IS-TFs を併用することで，平面波近似の妥当性を正確に評価できるようになった。

(4)柿岡地磁気観測所の電磁場データから(2)の手法を用いて時間的に変化する MT 応答関数を導出するとともに，(3)の手法を用いて磁場変動の空間勾配を求め，電離層電流の流れる場所に依存した MT 応答関数の変化を除去した。それによって得られた MT 応答関数の時間的変化は，観測点周辺の地質構造や周波数間での同期性などを考慮すると，降雨による地下浅部の比抵抗変化に起因することを特定できた。

以上，本論文で開発された手法は従来の大きな問題①・②を解決し，ノイズを多く含んだ自然の地磁気変動データからでも，短期的に生じる比抵抗構造の微小な時間的変化を明らかにできた。この技術は，比抵抗構造の計測精度，および比抵抗変化の時間分解能の向上にも貢献するので，エネルギー資源探査，地熱貯留層や帯水層のモニタリング，活断層の深部構造と地震発生との関係解明など，種々の地球科学・工学的課題の解決に資する研究として，学術上，実際上寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，令和 3 年 2 月 22 日，論文内容とそれに関連した事項について試問を行い，申請者が博士後期課程学位取得基準を

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満たしていることを確認し，合格と認めた。

なお，本論文は，京都大学学位規程第 14 条第 2 項に該当するものと判断し，公表に際しては，当該論文の全文に代えてその内容を要約したものとすることを認める。