直流電流により生じる岩石試料表面の電位イメージング

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DC potential imaging of a granite surface

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We are planning to perform resistivity imaging of small-scale (~10cm) rock samples. Resistivity imaging of objects with geophysical scales (~100 km) have been carried out for quite a few targets. However, it is unclear how the resistivity structures with such scales are quantitatively related with mechanical structures including fractures and cracks. In contrast, mechanical structure of rock samples with laboratory scales (~10 cm) can be directly observed. For this reason, resistivity imaging of rock samples possibly clarifies quantitative relationship between mechanical structure and resistivity structure.

To achieve resistivity imaging, it is necessary to inject electric current into a resistive rock sample and to measure the potential distribution on it. In our previous works, we have established a high-density electrode arrangement on surface of rock samples.We measured the potential distribution by using electrometers with a high input impedance of over 200T ohm (Suzuki et al ., 2017, JpGU). However, obtained values of voltages have not been stable, possibly because of two reasons. First, current intensity of the injected current (over 1nA) to the sample is not very stable. Second, injected current is leaked through an electrometer.

In the present work, we have made the following two improvements to the measurement of voltage distribution. First, we use a new direct current source with a maximum voltage of 110 V that can control intensity of the current with an accuracy of a few nA. Second, we use differential measurement method to prevent leakage current through the LO terminals of electrometers.In differential measurement, HI terminals connected to potential electrodes and each LO terminal is connected to LO terminal of current source. Because the input impedance of HI terminal is much higher than insulation resistance between LO terminal and ground, we can expect no leakage current from terminal of electrometer. We also use Guarding to remove leakage current through cable. In the Guarding, the signal line is surrounded by a conductor with high impedance. By keeping the voltage of the surrounding to the signal voltage, leakage current is avoided.

Abovementioned improvements of measurement method produce the following result. Intensity of the direct current injected to a rock sample are kept stable during more than one hour with the order of 10~30 nA. Leakage current is prevented by the differential measurement, which is confirmed by a fact that there was no leakage current from the HI to LO terminal of the current source. The time required for the measured values of potential differences to be stable is reduced to several ten seconds.Because of these improvements, we have succeeded to obtain measurement values of the potential with high precisions.

本研究では岩石試料 (〜10cm 程度) の比抵抗イメージングを目指している。大地（〜100km 程度）の比抵抗イメージングは極めて多く行われているが、実際の大地において比抵抗構造が破砕や空隙をどう反映しているのか確認することは難しい。ゆえにそれらの対応関係は明らかでない。一方、岩石試料は内部構造の直接的な観察が可能であるから、岩石試料の比抵抗イメージングが実現すれば、比抵抗イメージと内部構造の対比が可能になると期待できる。

比抵抗イメージングの実現には、岩石試料への電流印加と印加電流により生じた電位分布の測定が必要である。我々はこれまでに試料表面に高密度で接着できる電極を開発し、高入力インピーダンス (200T Ω以上) のエレクトロメーターを用いた電位分布の測定を試みてきた (鈴木、2017、JpGU など)。しかし、以下に挙げる課題が残った。1) 試料への安定した 1nA 以上の電流印加、2) エレクトロメーターを介した漏えい電流の防止。正しく電位分布を測定するためにはこれらの課題を解決する必要がある。

そこで、以下の工夫を取り入れて測定手法を改善し、前述の問題解決を試みた。まず、最大印加電圧 110V に対し数 nA 単位で電流量を制御可能な高精度電流源を導入した。また、2 台のエレクトロメーターを用いる差動測定法を用いて、漏えい電流を防止した。差動測定とは、エレクトロメーター 2 台の負極を電流源の負極と短絡させ、200T Ω以上の高入力インピーダンスが保証される正極 2 つを電位電極につなぐ手法である。それぞれの測定値の差から電位差が求められる。加えて、ガード測定により測定ケーブルを介した漏えい電流を取り除いた。ガード測定とは、信号線の周りを信号線と同電位に保たれた導体で取り囲む測定手法である。信号線の外側に対して電位差が生じなくなるため、電流は流れない。

上記の方法を用いて測定手法を改善した結果、以下の成果を得た。まず、高抵抗な岩石試料に対し、数 10nA オーダーの印加電流量を 1 時間以上安定して印加することができた。また、エレクトロメーターを介した漏えい電流を無くすことができた。電流源の正極から負極までに電流の損失がないことを確認した。そして、電位電極を付け替える際、数 10 秒のスケールで電位差が安定するようになった。これらの改善により、異なる複数の日に測定しても、高い再現性を示すようになった。電位分布は安定して測定できているものと考えられる。

岩石試料の比抵抗物性データベースの構築

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Construction of resistivity property database of rock samples

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Electrical and electromagnetic methods that survey subsurface resistivity structure are used in many fields such as resource investigation, disaster prevention investigation and scientific investigation. This is because the range of the resistivity of rocks and soils is considerably wide and difference in the feature of the target geologic structure is expected to be reflected in resistivity. The resistivity of rock is generally interpreted by the empirical formulas such as Archie's law, which relates the resistivity of a rock to its porosity, the resistivity of its pore water (fluid) and the water saturation. Since the resistivity of water changes at salinity and temperature, the resistivity of rock changes with the environment where the rock exist. It is known that the resistivity of the rock containing clay minerals is lower than the value generally estimated from Archie's law. The resistivity of the metallic ore is not applicable for the Archie's law because many of metallic minerals are a good conductor or a semiconductor.

In order to interpret the resistivity structure obtained from the electrical and electromagnetic methods, it is necessary to know resistivity of many rocks which form various geologic structures. Therefore, the construction of resistivity property database of rock samples are stated in the National Institute of Advanced Industrial Science and Technology (AIST). In this database, the complex resistivities of rock and soil samples measured in AIST are recorded with the measurement conditions. Other physical properties such as density, porosity and susceptibility, and geologic and geochemical information are also recorded as much as possible. It is thought that the resistivity property database becomes a powerful tool for utilizing the result of resistivity structure survey if the contents are enhanced.

地下の比抵抗構造を求める電気・電磁探査は、資源探査、防災調査、学術調査など多くの分野で使用されている。これは、岩石や土壌が示す比抵抗の範囲が広く、調査の目的となる構造の違いが比抵抗に反映されやすいからである。比抵抗は水の存在や温度に敏感な物性であるということがあげられる。一般的な岩石では、電気伝導は間隙中に存在する水などを媒体としたイオン伝導が卓越する。アーチーの式は岩石の比抵抗を説明する代表的な実験式であり、その比抵抗を間隙率と間隙中に含まれる水の比抵抗とその水飽和度で関係づけている。水の比抵抗は塩分濃度や温度で変化するので、岩石のある環境によって比抵抗は変化する。また、粘土鉱物を含有する岩石の比抵抗は、一般にアーチーの式から推定される値より低くなることが知られている。金属鉱石も鉱物が良導体や半導体であるので、その比抵抗はアーチーの式などの実験式は適用できない。

したがって、電気・電磁探査から求まった比抵抗構造を解釈するためには、地質構造を形成する種々の岩石や土壌の比抵抗を知る必要がある。そこで、産総研では比抵抗物性データベースの構築に着手した。このデータベースでは、産総研で測定されてきた岩石・土壌試料の複素比抵抗を測定条件ともに記録している。また、密度、間隙率、帯磁率などの物性情報や、試料の地質学記載や化学分析結果などの情報もできる限り記録するようにしている。その内容が充実するほど、比抵抗物性データベースは電気・電磁探査の結果を活用するための強力なツールになると考えられる。

薄層球殻による電磁シールド問題の球座標における数値解法

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Electromagnetic Shielding by Conducting Spherical Shell of Infinitesimally Small Thickness

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Since the mid-1990s, several simulators for global EM induction in a 3D sphere have been developed on the basis of the finite difference method (FDM) or the finite element method (FEM or the edge-based FEM) (e.g. Everett and Schultz, 1996; Maritinec, 1999; Uyeshima and Schultz, 2000; Yoshimura and Oshiman, 2002). However, in those simulators, a thin sheet approximation, which is very useful for modeling ocean distribution on the surface of the Earth, is not implemented.

EM induction studies using a thin sheet approximation of conductor have been made since Price(1949). Most of all thin-sheet numerical modeling with finite electrical conductivities for global electromagnetic induction are based on the methods of quasi-analytical solutions after representing the EM fields in terms of toroidal and poloidal potential. Kuvshinov and Pankratov(1994), Koyama and Utada(1998), Kuvshinov et al.(1999), and Sun and Egbert(2012) developed numerical solvers for global EM induction including a surface thin sheet cell structure.

There are very small numbers of numerical approaches to thin sheet modeling based on solving the differential equation in the spherical coordinate systems. Rikitake(1992) proposed numerical methods to solve EM induction problems of axially symmetrical cases of finite electrical conductivity distribution in a thin sheet, such as a spherical shell having a hole, including the potential value at the origin of the spherical coordinates. However, due to the power of the computer, only a few calculation results were shown in Rikitake(1992).

I extended the method proposed by Rikitake(1992) in order to solve problems of full 3D induction modeling of thin sheet spherical shell, namely cases of non-axial and non-uniform distribution of the electrical conductivity of the thin sheet shell. In this presentation, I will show results of electromagnetic shielding by non-axial symmetrical and non-uniform shell of a finitely conducting thin sheet, together with results of axially symmetrical cases.

1990 年代半ばごろから、グローバルな 3 次元電磁誘導のモデリングのための様々な数値シミュレーターが提案されてきた。例えば、Everett and Schultz（1996）、 Maritinec（1999）、 Uyeshima and Schultz（2000）、Yoshimura and Oshiman（2002）である。これらは電磁誘導の方程式を差分法、有限要素法、辺要素有限要などの手法を用いて解くものである。しかし、これまでに開発されてきたこれら一連のシミュレーターでは、地球表面の海陸分布などをモデル化するのに威力を発揮する薄層近似を、モデルの中に取り込むことまでは至っていない。

一方、薄層の電磁誘導問題に関しての理論的研究は、Price(1949) の成果にそのルーツをさかのぼることができるが、グローバルな薄層球殻を構造に含む電磁誘導問題の解法としては、求める場をトロイダル成分とポロイダル成分に分離したうえで、積分方程式法を基にして解くというような手法が主として活用されてきた。例えば、Kuvshinov and Pankratov(1994), 小山・歌田 (1998), Kuvshinov et al.(1999), また、最近では、Sun and Egbert(2012) などで、モデルの表面上に薄層球殻の電気伝導度構造を設定することが可能である。

Rikitake(1992) は、有限な電気伝導度の軸対称薄層球殻モデルを、差分法を基にして、Price(1949) に示された方程式を、差分法を基礎として数値的に直接解くことを行っている。このモデル解法では、薄層球殻内部は、電磁伝導度構造を持たない真空領域として扱われているものの、グローバルな電磁誘導問題を解くために、微分的手法を基礎とした解法（差分法、有限要素法など）に係わる研究推進のためには、非常に適した課題であると考える。そこで筆者は、数年前からこの解法に係わる研究を行ってきた。すでに Rikitake(1992) が扱った軸対称問題に関しての解法に係わる問題点とその解決法に関しては、2015 年度の CA 研究会でもすでに報告したが、今回は、適応範囲をさらに広げた計算プログラムを開発したので、それによる非軸対称薄層モデル、および、非軸対称不均質伝導度薄層モデルに関しての結果を報告する。

ACTIVE の結果を用いた三次元インバージョン：2014 年 11 月阿蘇山マグマ噴火に伴う比抵抗構造変化の推定

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3-D Inversion using ACTIVE data for temporal change in resistivity structure beneath Aso volcano through magmatic eruptions

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Magmatic eruption occurred in Aso volcano on November 25, 2014, for the first time since the last one 21 years before. The magmatic activity continued until the crater bottom collapsed in May, 2016. Since the explosive eruption on October 21, 2016, the volcanic activity of Aso volcano have been quiet. Before and after the magmatic eruption in November 2014, ACTIVE system (Array of Controlled Transient-electromagnetics for Imaging Volcano Edifice; Utada et al., 2007) was operated to monitor the activity. The system consists of a transmitter and several induction-coil receivers that detect the vertical component of the magnetic field affected by conductive anomaly beneath the volcano. By this ACTIVE system, temporal changes in responses were detected between observations in August 2014 and in August 2015. A previous one-dimensional (1-D) analysis revealed that a part at a depth of 100 to 150 m became resistive at the western rim of the crater. However, the 1-D analysis did not take the topography effect into account, which makes quantitative interpretation of the result difficult.

We developed new forward and inversion codes for ACTIVE responses, by adopting three-dimensional finite element method, and tried to infer temporal changes in resistivity structure which account for the obtained ACTIVE responses in August 2014 and August 2015. Topography was represented by tetrahedral elements where the numerical mesh was generated by a freeware, Gmsh (http://gmsh.info/). We adopted a kind of Heaviside function for the term of source electric currents (Ansari and Farquharson, 2014). To make our inversion scheme be a reasonable choice for eruption prediction system in the future, we applied the data-space inversion method (Siripunvaraporn et al., 2005) and adopted MPI parallelization in terms of frequencies so that dramatic reduction of the calculation time was achieved. Accuracy of our forward calculation was confirmed by comparison with an analytical solution for grounded long-wire electric current source problems (Ward and Hohmann, 1988). On the other hand, our inversion succeeded in determining a right position of conductive anomaly beneath the crater in a case where signals from three source wires are received at 20 receivers, which demonstrated accuracy of our inversion code.

We conducted inversions using the real ACTIVE data in a similar manner to the previous 1-D analysis, because, for full 3-D inversions, the number of receiver data points were quite few, i.e. four and three, for observations in August 2014 and in August 2015, respectively. Then we divided the model space 3 by 3 horizontally and conducted limited 3-D inversions with 3-D topography of Aso volcano. The obtained resistivity structures for before and after the magmatic eruption allowed us to investigate temporal changes through the eruption in November 2014. Our inversions revealed that at the western rim the part at a depth of 120 - 150 m from the surface beaome resistive, which corresponds to 1150 m in altitude and slightly below the altitude of the crater bottom. This result can be interpreted as escape of ground water during magma ascent in November 2014, as the previous 1-D analysis speculated. We plan to conduct sensitivity analyses and to confirm that the inferred temporal change is necessary for the observed temporal change in the ACTIVE responses.

In the presentation, we are going to explain the methodology of forward and inversion scheme tailored for controlled source problems especially for electromagnetic volcano monitoring like ACTIVE. Furthermore, we will discuss possible reasons for the inferred temporal changes in resistivity structure through the magmatic eruption in November 2014.

阿蘇山では、2014 年 11 月 25 日に約 21 年ぶりのマグマ噴火が発生し、火山活動が活発化した。以降、マグマ性の噴火は断続的に続き、2016 年 5 月に火口底陥没によりマグマ性の活動は終了している。2016 年 10 月 23 日に爆発的噴火があったが、その後現在まで、火山活動は静穏である。噴火のあった阿蘇中岳第一火口周辺では、2014 年 11 月のマグマ噴火前後に、火山体の電磁モニタリングシステム ACTIVE (Array of Controlled Transient-electromagnetics for Imaging Volcano Edifice; Utada et al., 2007) による観測が実施された。ACTIVE は、電流送信局から周期 1 秒の矩形波シグナルを送信し、地下の比抵抗異常の効果を受信局の磁場鉛直成分の変動として観測する手法である。この ACTIVE により、2014 年 8 月（マグマ噴火開始前）と 2015 年 8 月（マグマ噴火開始後）の間のレスポンスの時間変化が観測されており、先行研究による一次元解析により、火口西縁の観測点の地下 100-150m の領域で、構造が高抵抗に変化した可能性が指摘されている (第 131 回火山噴火予知連絡会資料その 4)。しかしながら、従来の一次元解析では、火口周辺の地形が考慮されておらず、比抵抗構造変化の位置と変化量の定量的な議論が困難であった 。

本研究では、地形効果を含めて ACTIVE データを解釈するため、有限要素法を用いた三次元の順計算・逆計算コードを開発し、2014 年 8 月-2015 年 8 月の比抵抗構造変化の推定を試みた。順計算では、四面体要素を採用し、フリーウェアの Gmsh（http://gmsh.info/）を用いて数値メッシュを作成した。ソース電流に関わる項はヘビサイド関数を用いて表現

している (e.g., Ansari and Farquharson, 2014)。逆計算（インバージョン）では、ACTIVE の噴火予測への応用を視野に、データ領域インバージョン手法 (Siripunvaraporn et al., 2005) の採用 、並びに、MPI による複数周波数計算の並列化を実施し、計算の高速化を実現した 。順計算の精度は、Ward and Hohmann (1988) による有限長電流双極子をソースとする問題の理論解を用いて確認した。また逆解析の精度は、3 箇所の送信局からのシグナルを計 20 受信局で受信した場合のインバージョンを行い、火口直下の低抵抗異常の位置が精度よく推定されることを確認している。

2014、2015 年の ACTIVE 観測では、前者で火口周辺に受信局が 4 点、後者では受信局が 3 点と、自由度の大きな三次元解析が難しい状況であった。そのため、本研究のインバージョンでは、水平方向には、モデル空間を３＊３の計９分割とし、一次元解析に近い状況で、各々のデータセットを用いた三次元インバージョンを行った。得られた２つの構造の差をとった結果、火口西縁の観測点の地下 120-150m の位置 (標高約 1150m) で高抵抗になる変化がイメージされた。この標高は、中岳第一火口の火口底の標高よりやや低い位置を示しており、これまでの一次元解釈と同様に、マグマの上昇が地下水を押しのけた効果であると解釈できる。今後、この構造における感度チェック等を行い、推定された構造変化の確度について調べる予定である。

本発表では、ACTIVE 等の人工電流を用いた火山体電磁モニタリングに適した有限要素法による順計算・逆計算手法を紹介する。加えて、2014 年 11 月のマグマ噴火前後の ACTIVE 観測結果から推定される阿蘇中岳の地下比抵抗構造の変化とその原因について議論する。

高次の積分方程式法による高精度電磁誘導フォワード計算コードの開発

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Novel "high-order" integral equation solver for electromagnetic sounding problems

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Electromagnetic (EM) methods are widely used in geophysics to model the subsurface electrical conductivity distribution. Conductivity is affected by rock type and composition, temperature, and fluid/melt content and thus can be used in various engineering and industrial problems such as detection of hydrocarbon (low-conductive) and geothermal or ore (high-conductive) reservoirs. Measured electrical and/or magnetic fields are further interpreted via calculations using a given three-dimensional model of the conductivity distribution.

However, still 3-D EM numerical simulations - which are a core part of any 3-D data analysis - with realistic levels of complexity, accuracy and spatial detail remain challenging from the computational point of view. To overcome this challenge the first-ever "high-order" solver for the volumetric integral equations (IE) of electrodynamics is presented. In contrast to previous IE solvers based on piece-wise constant approximation of the fields inside anomaly, the novel one is based on the piece-wise polynomial representation. Utilization of Galerkin method for constructing the system of linear equations provides not only guaranteed convergence of the iterative numerical solution, but also ensures that the system matrix is well-conditioned irrespective of the polynomials order.

The main computational challenge of presented approach is the computation of matrix coefficients i.e. the double volumetric integrals of the product between Green's function and polynomials. These challenge has been overcame by the generalization of the "quasi-analytical" approach proposed by first author for his previous IE solver, based on piece-wise constant approximation.

The numerical experiments demonstrate the possibility to decrease number of unknowns by several orders of magnitude with corresponding memory saving and speed up.

Two-Dimensional Inversion of Marine DC Resistivity Survey using FCM Clustering Constraint

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SMS (Seafloor Massive Sulfide) deposits, including rare and precious metals, have been often found in the vicinity of hydrothermal active areas: for example in the Okinawa Trough, Izu-Bonin arc, and Azores triple junction in the mid-Atlantic ridge. Geophysical explorations with electromagnetic (EM) methods are recently carried out around the SMS deposits in Papua New Guinea because the SMS deposits are known as low resistivity material. The resistivity distribution below the seafloor can be a good indicator for the buried SMS deposits. However, the resistivity structure below hydrothermal active areas has not been clearly investigated. In this study, we developed a 2D inversion of a marine deep-towed DC resistivity survey as an effective tool to the exploration of SMS deposits. The finite-difference method is applied in the forward modeling calculation to solve potential difference between the electrodes at the electric current injection to the seawater. The real distributions of SMS deposits are concentrated at narrow (thin) zones. Therefore, we add a guided Fuzzy C-Means (FCM) clustering constraint into the objective function in the inversion procedure in order to obtain sharp-change of resistivity matching the petrophysical information. Although the two balance parameters in this objective function should be controlled in the inversion, the optimal ways to adjust these parameters have not been proposed. Therefore, we propose an algorithm to choose these parameters properly. The new algorithm is based on the two stages; the first stage with the ordinary Occam scheme, then the second stage with the FCM clustering constraint where the inverted model in the first stage is used as the initial model in the second stage. The other parameters are decided with the searching scheme. The refined inversion results show that the inversion can produce sharp boundaries in resistivity structure, which can also handle with the realistic petrophysical information. Finally, we applied the inversion code to the field data obtained at the Okinawa Trough; the inverted resistivity anomalies are consistent with the known geological investigations of hydrothermal fluid flows and the observed distributions of seafloor venting sites.

MT法のサンプリング定理

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The magnetotelluric sampling theorem

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Here we consider a general case of Magnetotelluric (MT) study to reveal three-dimensional (3-D) distribution of the electrical conductivity within the Earth based on measurements of electromagnetic (EM) fields by a two-dimensional (2-D) array. MT array observation can be regarded as a sampling of MT responses (impedances), and each observation site can be regarded as a sampling point. This means that the array configuration must follow the sampling theorem. This paper discusses how the sampling theorem is applied to MT array studies, with special attention to the resolutions in the space and spatial wavenumber domains. Spatial Fourier transform of impedances in an array helps us to relate the EM scattering theory with spatial distribution of observed EM fields. The EM fields measured at a site are composed of their primary and secondary (scattered) components. The DC component of spatial Fourier transform relates the primary components of electric and magnetic fields. The scattered components are responsible for the spatially variable (AC) component of the impedance, and can be separated into signals that are resolvable by the array and noises (distortions) that are spatially too localized to be resolved. The regional (undistorted) field can be expressed by a combination of the primary component and signals of the secondary components. It is shown that an accurate estimation of the DC component is possible under the presence of galvanic distortion by using ssq rotational invariants. It is also suggested that the spatial and spatial wavenumber resolutions constrain a proper range of frequency for the analysis of MT array data.

周波数領域独立成分分析に基づく MT データのノイズ除去手法の開発

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Noise reduction method of MT data based ob Frequency Domain Independent Component Analysis

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Magnetotelluric (MT) method is one of the electromagnetic soundings to image deep subsurface resistivity structures. Electromagnetic data (MT data) often contain noises. The noises cause large errors in inferred MT response functions and to fail subsurface resistivity structure analysis. Recently, subsurface structure monitoring by MT method is conducted (e.g. Aizawa et al., 2011). In the case of high noise environment, temporal change of resistivity structure cannot be imaged clearly due to large errors in MT responses. Hence, noises must be removed properly. Conventionally, a robust remote reference processing (e.g. Chave and Thomson, 1987, 2004) is applied for noise reduction and estimation of MT response functions. However, a robust remote reference processing is less effective for MT data with continuous noises or coherent noise between electric and magnetic data. In this study, we focused on Frequency-Domain Independent Component Analysis (FDICA), which can decompose multi-component observed data into independent signals. FDICA and rrrMT (Chave and Thomson, 1987) were applied for MT data obtained at Kakioka Magnetic Observatory to check the reliability of our proposed method.

The outline of FDICA application for MT data was suggested by Sato et al. (2017). Four MT data (four components; electric and magnetic field of N-S and E-W directions) are decomposed into four independent signals (separated signals) by FDICA at each frequency. As a prior examination with Kakioka MT data, we estimated minimum SN ratio of magnetic field data by Gram-Schmidt orthonormalization, and confirmed SN ratio more than 1. Separated signals with high contribution to magnetic field data were considered as major MT signals. Conventional FDICA cannot separate noises and MT signals, which are not independent. In this case, separated signals considered as noises can contain MT signal components, and MT signals extracted by FDICA can contain noises. In order to overcome this, from such noise signals we removed spectrums with more power than median and recognized as minor MT signals. After this, stacking and remote reference processing are applied to reduce noises in MT signals by FDICA.

Raw MT data at Kakioka Magnetic Observatory during Feb.1 – Mar.16 in 2015 and during Mar.1 – Mar.16 in 2015 were analyzed. Former sampling rate is 1/60 Hz and latter is 1 Hz. FDICA and rrrMT were applied for the MT data, and apparent resistivity and phase curves were obtained. The apparent resistivity curves and phase curves by FDICA is almost same as ones by rrrMT, but estimated errors are much smaller than the case of rrrMT. However, at high frequency (around 0.1 Hz) and low frequency (lower than 0.1 mHz), the estimated errors by FDICA are as large as those by rrrMT. At low frequency, the longer MT data are processed, the smaller errors are expected to get. However, at high frequency, signal separation or signal judgment are failed. To verify FDICA performance, we added artificial noises to raw MT data at frequency with small error bars. As a result, only under two condition FDICA performance declined. First, magnetic field data have a low SN ratio. In this case, MT signals and noises cannot be distinguished properly. Another condition is noises strongly correlated with MT signals. Modifications of our code are necessary under these conditions. In this study, we developed new MT data processing method based on FDICA. The results were greatly improved compared with conventional method rrrMT. And condition for FDICA high performance was evaluated.

地磁気地電流法 (MT 法) は，電磁探査法の一種であり，地下深部の比抵抗構造の解析が可能である．しかし，取得した電磁場データにノイズが混入した場合，応答関数の推定誤差が大きくなり，地下の比抵抗構造のモデル化が困難となる．また，近年では MT 法を用いた地下比抵抗構造のモニタリングもなされている (例，Aizawa et al., 2011) が，ノイズが混入することで比抵抗の時間変動が推定誤差を下回ることも考えられる．そのため，電磁場データに混入したノイズを除去して，比較的短時間の時系列データから応答関数を導出する必要がある．従来は，Robust Remote Reference 法 (Chave and Thomson, 1987) によるノイズの低減がなされてきたが，電磁場データに共通し連続的に混入するようなノイズの除去は困難であった．そこで，多成分観測データから，独立な成分を抽出できる周波数領域独立成分分析 (Frequency-Domain Independent Component Analysis: FDICA) という手法に基づく，新たなノイズ除去手法を開発した．本研究では，気象庁柿岡地磁気観測所において取得された電磁場データに対し FDICA および従来法である rrrMT (Chave and Thomson, 1987) を適用した．

ここでは Sato et al. (2017) で提案した FDICA による MT データ解析についての概要を示す．取得された東西・南北方向の電磁場データ (合計 4 成分) に FDICA を適用することで，周波数ごとにそれぞれが独立な分離信号 (合計 4 成分) が得られる．そこでまず，取得した磁場データの SN 比が 1 以上であることを，Gram-Schmidt 法を用いて確認し，磁場データに対する寄与が大きい分離信号を主要な信号成分とみなすこととした．また，ノイズ成分と信号成分が完全に独立でないことがあり，FDICA によるノイズ成分と信号成分の適切な分離が困難となる．この問題を解決するため，ノイズ成分

と判断した分離信号中にも微小な信号成分が存在すると仮定し，ノイズ成分のうちで中央値以上のスペクトルを除去したものを信号成分として MT 解析に使用することとした．FDICA により抽出した信号成分にもノイズが含まれる可能性があるが，そのようなノイズは応答関数を導出する際に Remote Reference 法および Stacking 法を用いることで低減した．

気象庁柿岡地磁気観測所における電磁場データに対し FDICA および rrrMT を適用した．解析するデータは，1/60 Hz サンプリングの電磁場データ (2015 年 2 月 1 日から 3 月 16 日の 44 日間) および 1 Hz サンプリングの電磁場データ (2015 年 3 月 1 日から 3 月 15 日の 15 日間) である．これらの両期間の K 指数はともに 15 程度で通常の地磁気活動度である．また，Reference データとして同期間の女満別地磁気観測所における磁場データを使用した．rrrMT および FDICA を適用した結果，見掛比抵抗および位相は同程度であるが，FDICA を適用することで，応答関数の推定誤差が小さくなった．しかしながら， rrrMT および FDICA の結果において高周波数帯 (0.1 Hz 程度以上) や低周波数帯 (0.1 mHz 程度以下) ではエラーバーが大きいことも明らかとなった．

FDICA を適用して得られた見掛比抵抗曲線および位相曲線については，低周波数帯における推定誤差が大きいが，用いた MT データは 44 日間分という比較的短かい期間である．そのため，観測期間を延ばすことにより，低周波数帯における推定誤差の縮小が期待される．高周波数帯での推定誤差が大きい原因として，FDICA においてノイズ成分と信号成分の分離，またはその 2 つの判別が不十分である可能性が考えられる．そこで，応答関数の推定誤差が比較的小さい周波数帯に仮想的なノイズを様々な条件下で与えてみて，FDICA を適用することで，FDICA のノイズ除去性能を評価した．その結果，次の 2 つの条件のいずれかを満たす場合においてのみ，FDICA は有効でないことが明らかとなった．1 つ目の条件として，磁場データに対して大きなノイズが混入し，磁場データへの最大の寄与を持つ分離信号が信号成分ではなくなった場合である．この場合，信号成分とノイズ成分の判断が困難となるため，信号成分の分離が不十分となる．実際，高周波数帯においては，事前検討により推定した磁場データの SN 比の最小値は 1 を下回っていた．2 つ目の条件は，ノイズと信号成分の依存度が大きい場合である．以上より，高周波数帯 (0.1 Hz 程度以上) において FDICA のエラーバーが大きい原因は，磁場の SN が低く，また混入しているノイズが磁場信号に見掛上大きく依存していたためではないか，と考えられる．今後，これらの点に関する解析法の改善が必要である．

本研究では，FDICA を基に MT データからノイズを除去する新たな手法を開発した．我々が提案した手法を適用することで，従来法 (rrrMT) に比べ，見掛比抵抗曲線および位相曲線の推定誤差が小さくなった．また，本手法が有効な条件についても評価することができた．

ディープラーニング技術を用いた複数観測点データを入力とした高精度地磁気推定

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Deep Learning Technology Based High-Accuracy Geomagnetic Prediction Using Multi Site Observation Data

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As a result of continuous geomagnetic observation in our research group, we reported that small geomagnetic signal generates at the moment when the earthquake occurred.

In the Iwate-Miyagi Nairiku earthquake of 2008, we have presented successful observation of co-faulting Earth's magnetic field changes. The magnetic fields began to change almost simultaneously with the onset of the earthquake rupture and grew before the first P wave arrival. The geomagnetic signal changes was about 100 pT, which is a very small.

Moreover, observation results of Earth's magnetic field changes caused by tsunami effects from the 2011 Tohoku earthquake are reported.

To discuss a feasibility of new systems for a super-early warning of destructive earthquakes using measurement of EQ-piezomagnetic effects and/or early warning assist system of destructive tsunami using magnetic measurements, we have important problems to be solved. Then we introduced an estimation method of geomagnetic changes using deep learning technology.

In this presentation, we examine deep learning technology based geomagnetic field prediction method using multisite observation data as input signals.

We have tried to predict the geomagnetic signal at our geomagnetic observation point in Iwaki, Fukushima. Through our examination, we have confirmed that the accuracy of geomagnetic prediction is improved by use of multi-input to one output deep neural network.

我々の研究グループにおけるこれまでの研究結果として，地震発生したその瞬間に地震断層運動に伴う微小な地磁気信号が生じることが分かっている．

例えば，2008 年の岩手・宮城内陸地震において，震源に近い観測点では地震発生時刻から観測点まで地震波が到来するよりも先に地磁気信号が一方向に向かって変化しつづけた．

地磁気信号の変化量は 100pT 程度であり，非常に小さな信号であった．

また，津波発生時においても地磁気信号の変化が生じることがわかっている．このような地磁気信号は東北地方太平洋沖地震によって生じた津波発生時に観測された．津波の規模と観測点によって異なるものであるが，数 nT 程度の変化が予想される．

どちらの地磁気信号に関しても，それぞれの地磁気信号の検知をすることで，緊急地震速報や津波警報の高精度，高速化につなげることができると考える．しかしながら，これらの地磁気信号は小さく，自動検知を実現するためには解決すべき問題がある．

我々の研究グループでは，連続地磁気観測を通して，大規模データと呼べる観測結果を得ることができた．そこで，我々は，近年の計算機技術とアルゴリズムの発達により実現が容易になったディープラーニング技術に着目し，この技術をベースとした地磁気信号推定を報告した．

大規模な地磁気の観測データはディープラーニングに対して有効であるものと考える．

本発表では，ディープラーニング技術を用いた複数観測点データを入力信号として用いた地磁気推定結果を報告する．

我々は，地磁気の高精度な推定を複数の観測点における地磁気観測結果をデータ入力とし，我々の研究グループで保有する福島県いわき市地磁気観測点の地磁気信号推定を試みた．

ニューラルネットワークを用いて入出力が 1 対 1 である地磁気信号推定に対して，複数観測点を入力とし，出力を単一の観測点であるニューラルネットワークを用いたモデルによる地磁気推定の精度が大きく向上した．

Preliminary results for the estimation of the tides in the geomagnetic field

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Magnetotelluric (MT) studies at periods from 10^4 to 10^5 seconds suffer the violation of 'the plane wave source assumption' because of the Sq variation (the ionospheric tide) and the oceanic tide. Those tides are often approximated as a group of sinusoidal waves and are removed from the geoelectric and geomagnetic field data by the least squares fitting so that a usual MT procedure can be applied to the residuals of the geoelectric and geomagnetic fields. However, the MT response functions tend to scatter at periods from 104 to 105 seconds after the sinusoidal tidal variation is removed. Shimizu et al. (2011) attribute that to remains of the Sq variation. In fact, the Sq is known to show day-to-day variations and long-term variations.

I attempt to estimate the tidal variation in the geomagnetic field at Kakioka by the use of the robust Kalman filter procedure developed by Fujii et al. (2015). The procedure can decompose time series data into a roughly periodic variation and a long-term trend. I test whether the roughly periodic term can accommodate the tidal variation.

The geomagnetic field data used in this study are a four-year segment of the hourly values from 2002 to 2005 observed at Kakioka. The period of the periodic term is 24 hours to contain the Sq and its harmonics as well as the oceanic tides if necessary.

The parameter to control the periodic term is the variance of the periodicity s^2. If s^2 gets larger, the periodicity is loosened. As three cases of $s^2=10^{-4}$, 10^{-2}, 10^0 are tested to the three vector components of the geomagnetic field, all cases fit the data better than the convectional sinusoidal model. The case of $s^2=10^0$ shows the best fit indicating that the tides are not strictly periodic or the period used is inadequate. However, the large s^2 cases contain rapid fluctuations and, as a result, they include variations of the magnetospheric origin, too. I choose the case of $s^2=10^{-4}$ as an optimum model of the tidal variation because it seems to include no magnetospheric variation.

The optimum model has some evident differences from the conventional sinusoidal model. For instance, the amplitude of the optimum model gets smaller with year, which is consistent with the solar activity. In addition, the optimum model shows less rapid fluctuations. These results imply that the day-to-day variation and long-term trend of the Sq is not fully represented by the conventional sinusoidal model and the residual of the geomagnetic field includes remains of the Sq variation.

VTM と OBEM の観測による西之島火山のマグマだまりの推定

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Magma chamber beneath Nishinoshima volcano estimated by VTM and OBEMs observation

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We conducted electromagnetic observation on the seafloor around the Nishinoshima using 1 VTM (Vector tsunameter) and 4 OBEMs (Ocena bottom electromagnetometers) from October 2016 to May 2017. VTM got the data during the whole of this time, while OBMEs observed for a maximum of two months. The eruption activity of the Nishinoshima Island had not been identified during the first two months, the tilt data of VTM and OBEMs changed from 13th November to 20th November. At the same time, the total magnetic intensity changed a lot at two sites which were settled on the north side (NS03) and east side (NS04) the island.

Tilt data can include both crustal movement and instrumental movement itself, but there is no significant instrumental movement except a OBEM at NS06 according to the record of three-component fluxgate magnetometer. The tilt changes occurred in the middle of November were recorded at four sites, which means that the tilt changes were caused by crustal movement.

The differences of the total magnetic intensity were calculated at each site using N02 (VTM), which is the farthest site from the Nishinoshima, as a reference site. Whereas the total magnetic intensity of the north site (NS03) increased, that of the east site (NS04) decreased. These variations were about 10 nT, and these changes were consistent with thermal demagnetization occurred inside the island.

The large variations of the tilt and total magnetic intensity were related to volcanic activity of the Nishinoshima and might be caused by the movement of magma. Moreover, the large variations were occurred five month before the Nishinoshima restarted eruption activity.

In this presentation, we will introduce the results from analyzing the tilt and total magnetic intensity variations to estimate the position and size of the pressure source and the source of thermal demagnetization, respectively. And we will also discuss the tilt and total magnetic intensity variations recorded by VTM after November 2016 when the large variations occurred.

Acknowledgement: We thank the scientific party, captain, crews of R/V Shinsei Maru (KS-16-16) and Keihu Maru (KS17-04 leg2) to deploy and recover the VTM and OBEMs. We used the observatory data on Chichijima of Japan Meteorological Agency.

我々は、2016 年 10 月から 2017 年 5 月にかけて、西之島周辺の海底に 1 台のベクトル津波計 (Vector tsunameter; VTM) と 4 台の海底電位磁力計 (Ocean bottom electromagnetometer; OBEM) を設置し、電磁気観測を行った。VTM については、全期間においてデータを取得することができたが、OBEM については、設置直後から最大約 2 ヶ月間データを取得することができた。5 台全てのデータが得られている約 2 ヶ月の間、西之島の噴火活動は確認されていないが、11 月 13 日頃から 11 月 20 日頃の約 1 週間の期間に、VTM と OBEM の傾斜記録に顕著な変動が見られた。また同時期に、西之島の北側 (NS03) と東側 (NS04) の 2 観測点において、顕著な全磁力の変動が認められた。

VTM および OBEM の傾斜計の記録は地殻変動と測器の動きとの両方を含み得るが、磁場 3 成分記録から推定される測器の回転角から判断する限り、北西側に設置した 1 台の OBEM(NS06) を除き、有意な測器の動きは認められない。11 月中旬の傾斜変動は、複数の点で観測されていることもあり、地殻変動によるものと考えられる。しかしながら、変動量は非常に大きく、北側観測点 (NS03) では 1 度近くにも及ぶ。

全磁力については、西之島から最も離れた NS02 点 (VTM) を参照点として差を求めると、北側観測点 (NS03) で正の変動、東側観測点 (NS04) で負の変動が見られる。変動量はそれぞれ約 10nT である。変動のセンスは、山体内部で熱消磁が起こったとの解釈と矛盾しない。

傾斜変動も磁場変動も西之島火山全体の火山活動に関わる大規模な変動であり、マグマの動きがこれらの変動に関係しているようである。しかも、これらの大規模変動は、西之島の再噴火が起こる 5 ヶ月前に観測された。

本発表では、傾斜変動と全磁力変動のデータから、それぞれ圧力源と熱消磁の位置や大きさを求めることによる、マグマだまりの深さや大きさの推定結果について紹介する。さらに、大規模変動が起こった 2016 年 11 月以降の全磁力変動・傾斜変動についても議論する。

謝辞：本観測における機器の設置・回収には、東京大学大気海洋研究所の共同利用による新青丸航海 (KS-16-16)、気象庁の啓風丸航海 (KS17-04 leg2) を利用した。また、参照点として気象庁地磁気観測所の父島観測点データを利用した。

Large-scale electrical resistivity structure around the long-term Slow Slip Events beneath the Bungo Channel

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Recent geodetic observations detect recurrent slow slip events (SSEs), which occurred beneath the Bungo Channel and southwest Shikoku Island, with interval of approximately 6 years (e.g. GSI, 2010). To reveal a large-scale three-dimensional resistivity structure around this SSEs region, we carried out wideband magnetotelluric (MT) surveys around the western part of Shikoku Island. As of June, 2016, MT surveys were performed at 31 sites by using Phoenix wideband MT instruments. In the most of sites, high quality MT responses were estimated using the BIRRP code (Chave and Thomson, 2004) for the period range 300 Hz to 10,000 sec (Yoshimura et al., 2016). In addition, we used 8 more MT and telluric data obtained for different purposes; 6 sites from the opposite side of the Bungo Channel, namely the eastern part of Kyushu Island, measured by Metronix ADU and NT System Design ELOG systems (Aizawa et al., 2017) and 2 sites from the region of the central part of SSEs measured by Phoenix MTU system (Okazaki et al., 2017). These additional data were also reprocessed by the BIRRP code. In this study, we totally used 38 sites for a three-dimensional inversion.

Using obtained MT responses, we constructed a three-dimensional resistivity model around the SSE region. We inverted the impedance tensor and the vertical magnetic transfer function by the "femtic" inversion code developed by Usui (2015). The "femtic" inversion code employs the edge-based finite element method for unstructured tetrahedral elements and estimates the subsurface resistivity structure and the distortion tensor for each observation site. The main features of the preliminary three-dimensional model are 1) a moderate conductive zone in the central part of SSEs 2) whose trenchward extension shows more conductive and 3) conductive zone surrounding the SSEs regions. These results suggest that the lateral electrical heterogeneity could have controlled the slip distributions of SSEs along the upper boundary of the Philippine Sea slab.

再解析 Network-MT データによる別府-島原地溝の 3 次元比抵抗分布モデル

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3-D electrical resistivity distribution beneath the Beppu-Shimabara graben by reanalysis Network-MT data

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We performed a three-dimensional (3-D) inversion analysis by using a data set of network-magnetotelluric (network-MT) data in a period range from 640 to 10,240 s to obtain a subsurface electrical resistivity distribution around the Beppu-Shimabara graben in Kyushu. Active Quaternary volcanoes, such as Aso with a caldera, Kuju, and Yufu, exist with an interval of ~20 km in the graben. Among the three volcanoes, Aso has been the most active volcano in recorded history. Aso caldera had been formed by a series of huge eruptions during 270-90 ka and post-caldera cones were formed in the caldera. A post-caldera cone of Naka-dake has repeatedly erupted since the 6th century. Thus, we especially focused on the resistivity distribution beneath Aso caldera. Network-MT surveys for the electric field (the electric potential difference) were performed around the graben from 1993 to 1998 by using long metallic wires/dipoles of the commercial telephone company′s networks [e.g., *Tanaka et al.*, 1998; *Hashimoto et al.*, 1999; *Uyeshima et al.*, 2002; *Hata et al.*, 2015]. We determined two components of network-MT response functions between the potential differences and the two horizontal components of the magnetic field, which were recorded at the long dipoles and at the Kanoya Geomagnetic Observatory respectively. Fifty dipoles, which were densely distributed in Aso caldera, were selected around the graben of 110 by 150 km in the north and east directions to obtain a 3-D resistivity model by using a data space Occam's inversion code modified for the network-MT data [e.g., *Siripunvaraporn et al.*, 2004]. The obtained 3-D resistivity model had significant conductive anomalies, which appeared at depths of less than ~10 km in Aso caldera and extended to a deep part of the crust beneath Kuju volcano. In this presentation, we will show in detail on the 3-D resistivity model.

2016 年熊本地震直前に現れた非移動性 MSTID

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Stagnant MSTID immediately before the 2016 Kumamoto Earthquake

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http://www.ep.sci.hokudai.ac.jp/~heki

We examined if detectable ionospheric anomalies preceded the foreshock (M_w6.2) and the mainshock (M_w7.0) of the 2016 April Kumamoto earthquake sequence, shallow inland earthquakes. We analyzed changes in ionospheric total electron content (TEC) using Japanese dense network of Global Navigation Satellite System (GNSS) receivers. We did not find anomalies of the kind we often observe before larger earthquakes (in contrast, we found a typical one before the Mw7.8 Ecuador earthquake on the next day of the Kumamoto mainshock). This supports the empirical relationship by Heki and Enomoto (2015) that sizes of the preseismic TEC anomalies depend on Mw and background vertical TEC, but not on maximum seismic intensities. We found that a stationary linear positive TEC anomaly, with a shape similar to medium-scale traveling ionospheric disturbance (MSTID), emerged above the epicenter ~20 min. before the Kumamoto mainshock. Unlike typical night-time MSTID, it did not propagate southwestward; instead, its positive crest stayed above the epicenter for ~30 min. This unusual behavior may reflect crust-origin electric fields, but further studies are needed to conclude.

Fig.1 (caption) The development and movement of an MSTID-like anomaly that appeared shortly before the Kumamoto mainshock (April 15, 2016), shown by five-minute snap shots with GPS Sat.6. We drew five gray lines with 100 km separation to visualize their propagation. Typical night-time MSTID should show southwestward movements of 80-200 m/s, but the positive crest of MSTID on this night was stagnant above the mainshock epicenter (black star).

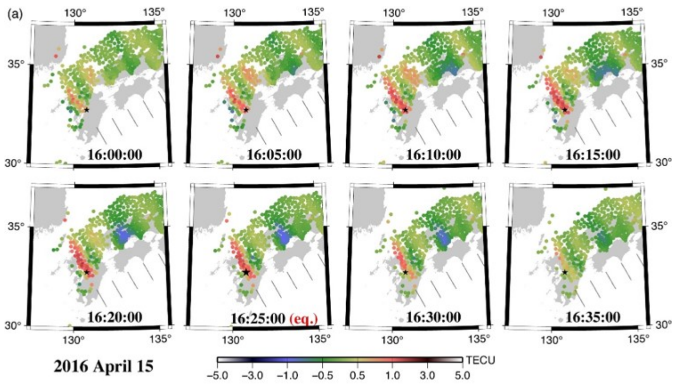
2011 年東北沖地震の 40 分前に始まった電離圏全電子数 (TEC) の変化は，Heki (2011 GRL) で最初に報告された．2013-2015 に JGR 誌上で三篇の批判的論文と，それらへの反論 (Heki and Enomoto, 2013; 2014; 2015) が行われた．それらの主な内容は，GNSS で見いだされた地震直前の TEC 変化が，(1) 地震後の音波擾乱による TEC 減少に起因する Artifact ではないこと，及び (2) 宇宙天気によるものではないこと，の二点に集約されるが詳細は繰り返さない．

2015 以後の我々の論文を概観すると，Heki and Enomoto (2015 JGR) では，M_w8.2 以上の 8 地震に関して前兆の大きさを Mw と背景 TEC に関係づける経験式を提案し，かつ先行時間と M_w の相関 (M_w9 で 40 分，M_w8 で 20 分) を示した．He and Heki (2016 GRL) は，チリで今世紀に発生した三つの大地震の直前に生じた正と負の電子密度異常の三次元構造が，Kuo et al. (2014 JGR) が示した地表電荷が励起する鉛直上向き電流による電子再配置と調和的であることを示唆した．また Kelley, Swartz and Heki (2017 JGR) では，地震前に地表に生じた正電荷が電離圏中に直接作る電場がもたらす ExB ドリフトによって，観測された正と負の TEC 異常が説明できるとした。最新の論文である He and Heki (2017 JGR) では，32 個の M_w7.0-8.0 の地震直前直後の TEC を解析し，VTEC の絶対値が非常に高い場合に限り M_w7 台の地震直前にも同様の異常が生じることを示した（先行時間は M_w7 で 10 分）．前兆を確認した地震は約 20 個となり， M_w と背景 VTEC の条件を満たす地震では，例外なく予測された場所と時刻に見いだされることが特徴である．力学的な地震の開始時に，その最終的なサイズがおおむね決まっていることは地震学的にも興味深い．ただし，M_w8 台後半以上の地震でないと地震発生前の検知は難しいだろう．

2016 年 4 月に発生した熊本地震（前震と本震）に関し，GEONET を用いて地震直前の電離圏全電子数 TEC を調べた．本震の M_w（7.0）と背景 VTEC（数 TECU）から，地震直前に観測可能な VTEC の折れ曲がりは出現しないことが予測され，そのことは He and Heki (2017) の解析でも確認されている（熊本地震本震翌日にエクアドルで発生した M_w7.8 地震では，予測通りの TEC 変動が確認されている）． しかし詳細な解析の結果，地震前後の同時刻帯に連日のように発生していた中規模移動性電離圏擾乱 (MSTID) が，本震直前に停滞するという珍しい振る舞いが見いだされたので報告する．ただし最後でも述べるように，この現象はまだ再現性が確かめられていない．

中緯度地域で夜間に見られる，NW-SE 走向の波面を持つ MSTID は，電離圏中の磁場と分極電場の相互作用で生じ，Perkins 不安定等で成長することが知られている．夜間 MSTID は通常南西に 80-200 m/s で伝搬する (Otsuka et al., 2011) が，伝搬メカニズムには不明な点が多い．熊本地震の前後も，毎晩のように SW に伝搬する典型的な夜間 MSTID が発生していたことが確認されている．本震 (Apr. 15 16:25 UT) の 20-25 分前にも北北西—南南東に伸びる 1 TECU 程度の正の帯が生じたが，震源直上に停滞するこれまでにない挙動を示し，地震約 10 分後に消えた（図 1）．M_w7.0 の本震直前に生じた地殻起源の電場は，He and Heki (2017) が示すように自力で電離圏電子を再配置するほど強くなかった．しかしその電場が不安定現象を通じて典型的な MSTID の走向を持つ帯状の電子密度異常の成長を促し，かつ電場の起源が地殻にあるため通常の MSTID のような伝搬が起こらなかった可能性が考えられる．

本仮説を検証するためには，(1) 夏の夜間に，(2)GNSS 局が稠密に展開された日本列島で，(3) ある程度大きな (M7 級以上) 地震が発生した例を複数集めて再現性を調べる必要がある．筆者は現在までにこの三条件を満たす他の例を見出すことができておらず，本現象も論文執筆の段階にはいたっていない．


(a)
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16:05:00
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2016 April 15
TECU
−5.0 −3.0 −1.0 −0.5 0.5 1.0 3.0 5.0

中緯度における中規模伝搬性電離圏擾乱について

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Medium-scale traveling ionospheric disturbances at mid latitudes

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Traveling ionospheric disturbance (TID) is a phenomenon of the electron density perturbations in the ionosphere. It has been considered to be the plasma manifestations of atmospheric gravity waves propagating in the thermosphere. Recent observations of airglow images and GPS receiver networks have disclosed two-dimensional horizontal structures of medium-scale TIDs (MSTIDs) which have horizontal wavelengths of several hundreds of kilometers. Most of nighttime MSTIDs propagate southwestward. This feature cannot be explained by the classical theory of gravity waves. Therefore, the nighttime MSTIDs could be associated with polarized electric field perturbations.

The ionospheric electric current in the F region are driven mainly by thermospheric neutral wind, and thus flows northeastward during nighttime because the neutral wind blows southeastward. Since the current traverses the perturbations of the plasma density, polarization electric fields could be generated to maintain divergence-free of the electric current. The polarization electric fields could be southwestward (northeastward) in the high (low) plasma density region.

Recently, it is suggested that the ionosphere is affected by earthquakes. In this presentation, we will review the mechanism for generating the nighttime MSTIDs, and discuss effects of earthquakes on MSTIDs.

電離圏には、伝搬性電離圏擾乱 (Traveling Ionospheric Disturbance; TID) とよばれる電子密度の粗密構造が伝搬する現象があることが従来から知られており、1960 年代より、この現象は大気重力波による中性大気の振動が原因であると考えられてきた。しかし、近年の光学・電波観測技術の発展によって TID の水平二次元構造や伝搬特性が明らかになると、夜間に発生する中規模 TID(MSTID) は電磁力学的な不安定によって生成されていることが明らかになってきた。特に、中性大気風が駆動する電離圏電流が MSTID による電子密度の空間不均一中を流れるとき、電流の連続性を保つために分極電場が生成され、その電場によるプラズマの ExB ドリフトが夜間 MSTID の原因と考えられるようになってきた。

北半球において、夜間における MSTID の発生機構は、以下のように考えられる。中性大気風は、高温な昼側から低温な夜側に向かって吹くため、夜間において南東方向に吹く。この中性大気風速により駆動される電流は、北東向きである。電離圏における電気伝導度は電子密度に比例するため、電子密度の粗密構造が存在すると、電流の一様性を保つため、電子密度の増大（減少）領域において南西（北東）方向の分極電場が生じる。この分極電場によるプラズマの ExB ドリフトは、プラズマを低 (高) 高度に輸送し、電子密度の粗密構造をつくる。

近年、地震に伴う電離圏変動が報告されており、MSTID への影響も議論されている。本講演では、MSTID の生成機構についてレビューするとともに、地震が MSTID に及ぼす影響の可能性について議論する。

巨大地震直前のTEC変動をもたらす地表の鉛直電流密度分布に対応した水平電場の定量的見積もり

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Evaluating horizontal electric field in the ground corresponding to TEC variatioin prior to mega earthquakes

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Vertical electric current from the ground to the atmosphere prior to mega earthquake in the epicentral area is discussed which is due to electric polarization or electric current source in the hypocentral area causing TEC variation above the epicentral area. While previous studies assume the vertical electric current density distribution on the ground, the present study discuss the feasibility of such mechanism by evaluating horizontal electric field and the Joule heat in the ground corresponding to assumed vertical electric current density distribution on the ground.

Horizontal electric field and the Joule heat are evaluated accompanying the vertical electric current density on the ground. The whole space is assumed to be composed of two half spaces which are isotoropic and homogeneous conductors. The electric current source is assumed to exist at a certain depth as a simple model. As is assumed in a previous study, the vertical electric current density on the ground is assumed to distribute in an area with 400km times 900km and its intensity 1-100nA/m^2 in maximum. Considering the electrical conductivity of the air and the ground as 10^{-13} and 10^{-2} S/m, respectively, the corresponding horizontal electric field and the Joule heat on the ground amount to 0.3-30kV/m and 0.9-9000kW/m^3, respectively. The scalar potential on the ground amounts to the order of GV. Considering the specific heat and density of typical rock, the heating on the ground amounts to 0.3-3000mK/s and larger in deeper in the ground.

The evaluation suggests that discussing the mechanism that TEC variation is due to the charge transfer from the ground to the ionosphere prior to mega earthquake should be discussed with expected accompanying phenomena such as horizontal electric field and the Joule heat.

巨大地震の直前に震央域上空で生じるとされるTEC変動の発生メカニズムに関する仮説として、地中の震源域における電流源から地表を通じて大気中への、震央域での鉛直電流が検討されている。先行研究は、地表から大気圏への鉛直電流密度分布を所与とするが、本研究はこの鉛直電流密度分布に対応する水平電場及び地中のジュール熱を定量的に評価し、このメカニズムの当否を検討する。

地表に仮定する鉛直電流密度分布に符合する地中の電流源の分布を求め、これによる地中及び大気中の電場及びジュール熱を評価する際、単純モデルとして空間には地中・大気ともに等方均質な導電体を仮定し、さらに地中の電流源分布は一定深度に水平な分布を仮定する。先行研究が仮定するように、地表の水平400km・900km四方に最大で1-100nA/m^2の鉛直電流密度分布を巨大地震直前の震央域に仮定する場合、大気と地殻の電気伝導度をそれぞれ10^{-13}及び10^{-2}S/m程度とすると、地表付近における鉛直大気電場は10-1000kV/mに相当するが、地表における水平電場及び地中側地表のジュール熱はそれぞれ0.3-30kV/m、0.9-9000kW/m^3程度となることが示される。地表の電位は無限遠方のゼロ電位を基準にして、地表の鉛直電流密度が極大となる地点で最大となり、GVオーダーとなる。さらにジュール熱から換算される、地表における地中側の熱源は、岩石の比熱と密度を桁で考慮すれば0.3-3000mK/s程度であり、地中深く地中の電流源に接近するほど大きくなる。

以上の見積もりからは、先の仮説に基づけば巨大地震直前に震央域においては水平電場の、通常の地電位差計測機器では測定が困難な著しい強化が、また特に地表における鉛直電流が大きければ震央域における地温や気温の有意な上昇が、関連する現象として想定される。震央域の地表における地中から大気中への電荷移動によってTEC変動がもたらされるとするメカニズムの仮説に対して、これらの関連現象が並行して議論される必要がある。

The affection of the scattering effect on the coseismic magnetic signals

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The coseismic electromagnetic (EM) signals associated with natural earthquakes have been reported in numerous field observations. Several numerical simulation works based on the electrokinetic effect have successfully explained some characteristics of the observed coseismic EM signals. However, there is one problem on the coseismic magnetic signals. When the receiver is nearby the ground surface, the simulated coseismic magnetic signals will show up as late as the arrival of S waves. That is obviously different from field observations, in which coseismic magnetic signals show up at the arrival of P waves. To explain this difference, we conduct theoretical analysis on the reflection and transmission coefficients at the ground surface, which implies the scattering effect probably has a significant contribution to the coseismic magnetic signal observed before the arrival of S waves. Thereafter, further numerical simulations are carried out to estimate the affection of the scattering effect on the coseismic magnetic signals.

海底 MT アレイデータと独立成分分析を用いた Sq 成分分離の試み

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[1] 東大・地震研

On separation of Sq field from seafloor MT array data using independent component analysis

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For estimation of electromagnetic (EM) response functions at the periods between 10^4 and 10^5 seconds from seafloor magnetotellric data, the effects of complex external source fields (e.g., geomagnetic solar quiet daily variations (Sq) and tides) are necessary to take into account. One of the ways to deal with this problem is to determine the amplitude and phase of time variation of observed field for known periods of Sq and tides and to subtract them from the data. However, the reduction of the effects seems not enough to obtain reliable EM responses (Shimizu et al., 2011).

In this study, we apply independent component analysis (ICA) to separate Sq field from the observed magnetic data. Sq field is based on the current in the ionosphere, which is excited by heating by Sun. Then, we may suppose that instantaneous mixing model can be applied by treating the data with local time of each station. We applied the ICA to the seafloor MT data collected from the Philippine Sea for about one year from November 2005. For detecting Sq component, we investigated the detailed time variation and power spectrum of each independent component and correlations of mixing coefficients to longitude and latitude, to detect Sq related components. We will demonstrate the detail of the analysis and discuss the feasibility of the source separation and better EM response estimation.

海底 MT データより電磁気応答関数を推定するに当たり、10^4～10^5 秒の周期帯においては、複雑な外部磁場ソース（地磁気静穏日日変化 (Sq) や海洋潮汐など）の影響を考慮する必要がある。従来は、時系列データから既知の周波数の変動分の振幅・位相を最小二乗的に推定して差し引くことが行われているが、電磁気応答関数は十分な精度では求まらず、Sq 場などの除去が不完全であることが影響していると考えられている（Shimizu et al., 2011)。

本研究では、多変量解析手法の一つである独立成分分析を海底 MT アレイデータへ適用し、Sq 成分を観測データから分離することを試みる。Sq は、電離層が太陽によって温められる効果を反映した電流系によっているので、アレイデータを各観測点の経度にあわせたローカル時間で揃えることにより位相差を考えなくて良いとすると、最も単純な信号混合モデル（信号が時間遅れ無しに混合する）を適用できる。予備的な解析として、フィリピン海で 2005 年 11 月から約 1 年間同時観測した海底 MT データに適用した。分離した独立信号から Sq に関連した成分を特定するために、各信号の時間変動の特長のほか、パワースペクトルや、混合係数の緯度・経度との相関を参考にした。本発表では、その詳細を示し、Sq 場分離の実現可能性と、電磁気応答関数の推定精度向上の可能性を議論する。

異方性層構造における MT 応答関数の周波数展開

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Frequency Expansion of MT Impedance Tensor for Anisotropic Layered Media

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The recursion formula of the impedance tensor is known for 1-D anisotropic layered media (Pek and Santos, 2002). This formula involves matrix operations, so it is difficult to perform analytic calculations except for a few number of layers. Okazaki et al. (2016) conducted frequency expansion of the impedance tensor for any layered structure at the first order, which describes the long period behavior of the MT response. By applying this formula to dimensionality analysis, they discussed the dependence on subsurface parameters and physical meaning.

This presentation improves the above algorithms. We derive the second order formula to deal with dimensionality analysis in more detail. We see that higher order expansion requires more and more tough calculation because the coupling between layers exponentially complicates. Finally, we discuss the difference in the form of real and imaginary part to extract subsurface resistivity structure from long period behavior of the impedance tensor.

異方性媒質が含まれる 1 次元成層構造において、インピーダンスを計算する帰納公式が知られている (Pek and Santos, 2002) が、この公式は行列演算を伴い、層の数が少ない場合を除いて解析的に計算を実行することは困難である。そこで Okazaki et al. (2016) では周波数の 1 次まで展開することで、任意の層構造でインピーダンスの長周期での振舞いを記述する公式を導出した。その表式に次元判定を適用し、地下構造のパラメータへの依存性とその物理的意味を議論した。

本発表では、上記の展開を簡略化した計算方法を紹介する。これを用いて 2 次の展開公式を導出し、次元判定をより詳細に扱う。さらに高次の展開を考察し、次数が上がるにつれて層間の関係性が幾何級数的に複雑になることを見る。最後に、展開の一般形に表れるインピーダンスの実部と虚部の差異に着目し、応答関数の長周期の振舞いから地下の比抵抗に関する情報を得る手段について考察する。

ロシア・バイカル湖における電磁気モニタリング

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Electromagnetic monitoring of the Lake Baikal

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Being the deepest lake in the World, a unique active rift structure - a nascent ocean, the Lake Baikal is a huge natural laboratory for different studies. The vertical component of electric field Ez in the hydrosphere can be free from telluric interference and therefore it is of particular interest for monitoring purposes. This idea has been implemented in the long-term Baikal experiment. This experiment is aimed at the studies of the water transport, the hydrosphere segment of the Global Electric Circuit (GEC) and the earthquake precursors. The monitoring of Ez on the basis surface-to-floor started in the southwestern part of the Lake Baikal in 2003. In 2012 a novel setup, providing the facilities to control the self-potentials of electrodes and other possible noise sources, has been put into operation. This setup in the configuration, includes, besides Ez, the measurements of sea currents and magnetic field (and its gradient) on the shore.

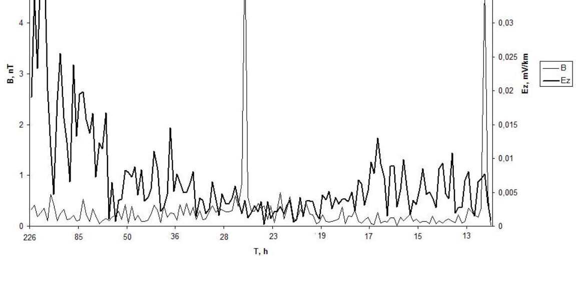
The experiment has confirmed absence of the telluric component in Ez. Fig. 1 shows an example (2013/2014) of comparison of the spectrum Ez and magnetic field modulus B received by simultaneous measurements by the nearest magnetometer. Clear and large first and second harmonics of the diurnal variations in the spectrum of B do not have any response in the spectrum of Ez. On the contrary, the characteristic features of the Ez spectrum have no correlation in the B spectrum.

The characteristic features of the Ez spectrum reflect the strongest (synoptic) sea currents in the Baikal within a period of 2-10 days with a random spectrum and the sole periodic sea current with a period of about 15 hours. Due to the fact that Ez, measured on a long base, does not depend on either the geoelectric section or on the flow structure, it’s attractive for the monitoring of the integrated sea currents velocity, important for hydrology, but rarely practiced because of its highly cumbersome implementation by direct methods.

At the periods longer than 10 days the sea currents in the Lake Baikal are very weak. However, unexpected strong Ez variations were discovered at the periods 100-160 days, which could not be motionally induced. We interpret it as manifestation of the GEC current on its hydrosphere segment: the X-ray variation influents on the ozone layer, which slowly causes the convective current variation in the troposphere and then the conductive current variation in the hydrosphere.

On August 27, 2008, 1h 35m UT the earthquake of magnitude M=6.4 happened near the setup. The depth of the hypocenter was 17 km; the distance from epicenter was 16.4 km. The fast amplification of negative Ez began 15 hours ahead of the earthquake. The amplification of the field by 25 microV/m ends with the extremely sharp separate splash, which is induction effect of tsunami wave, emerged exactly at the earthquake instant. The magnitude of the splash 9 microV/m corresponds to the magnitude of the water velocity about 50 cm/s, which is a quite real estimation of emerged small tsunami. Thus we observed the results of two different field excitation mechanisms: 15-hours precursor caused obviously by electrokinetic mechanism (at amplification of deep underground water filtration before the earthquake), and practically instantaneous induction tsunami effect.

Considering the complex character of electromagnetic monitoring, with planned extension of the observation network, detailed knowledge of the geoelectric cross-section over entire Baikal Rift is required. Therefore a preliminary detailed 3D geoelectric model of Baikal and the entire surrounding land has been constructed on the base of all available geoelectric and other geophysical and geological data. This model has helped to clarify some geological views by Ez monitoring and can serve as a basis for future areal regional and detailed magnetotelluric studies.



2000年三宅島噴火における傾斜ステップに伴う地磁気変化の再検討

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Magnetic changes accompanying tilt-step events during the 2000 eruption of Miyake volcano revisited

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A new caldera was formed at the summit during the 2000 eruption of Miyake-jima Volcano, central Japan. It began with the collapse on the top and was finally built up until the August 18 largest eruption. During the caldera formation, the ground deformation called the tilt-step occurred once or twice a day. The velocity wave form of the tilt-step was the seismic VLP event with 50 seconds duration. Although the amplitude of VLP event was different one by one, its duration was always constant. Associated with the tilt-step events, the geomagnetic and electric field variations were observed. The magnetic change was an abrupt step-like one similar to the tilt-step itself, while the SP variation had a single wave form with 100 seconds duration. Two different models were proposed for the generating mechanism of the tilt-step, i.e. Kumagai model (Kumagai et al., 2001: a cylindrical piston entering into the magma reservoir) and Kikuchi model (Kikuchi et al., 2001: underground explosion of a vapor reservoir injecting fluids into the surrounding rocks).

The total intensity changes were explained as due to the piezomagnetic effect accompanying the Mogi model. Forced injection of fluids produced the SP variation owing to the electrokinetic effect (Sasai et al., 2002; Zlotnicki et al., 2003). Currenti et al. (2005) obtained the best-fit parameters for the piezomagnetic Mogi source with the aid of the genetic algorithm. However, a new study on the cause of SP variation was presented by Kuwano et al. (2015), in which the fluid flow was induced within the poroelastic medium by the strain field of the tilt-step source. They employed the Kumagai model, which was approximated by a vertical tensile crack.

Recently, we obtained the 3-component magnetometer data at two sites MKK (NE) and MKT (SE) located on the eastern slope of Miyake-jima Volcano thanks to NIED. They are more precise (0.01 nT accuracy) and with higher sampling rate (1 Hz), which enable us to further investigate the generating mechanism of the tilt-step events. Based on new magnetic data as well as a different idea on the tilt-step proposed by Kuwano et al., we reexamined our previous model for the magnetic variations. We found that the Mogi model cannot explain the observed 3-component magnetic data. In particular, the D component variations at two stations are opposite in sign, which is one of the major defects in the case of the Mogi model.

However, 3-component magnetic data contain apparent changes owing to the rotation of the sensor in the geomagnetic main field, which are of the same order of magnitude as the piezomagnetic changes. Even if we take account of such apparent changes, the Mogi model cannot explain the observations, in particular those in the D and H component. A vertical tensile fault is preferable as the source for the observed magnetic changes both from the sensor rotation effect and of the piezomagnetic origin. Since flux-gate magnetometers fixed to the ground are widely used for tectonomagnetic studies, the apparent magnetic changes due to the sensor rotation should be carefully discriminated from true ””signals””.

成層媒質中の動的電磁誘導により生成される地震時電磁場変動

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Induced electromagnetic field by seismic waves in stratified media in Earth's magnetic field

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Seismic waves generate electromagnetic (EM) variations through a variety of mechanisms. The possible mechanisms include electrokinetic effect, motional induction effect, piezo-electric/magnetic effect, etc. Extensive studies have been carried out to calculate EM variations arising from each mechanism. Earlier studies suggest that the electrokinetic effect is a major mechanism. Numerical simulations assuming the electrokinetic effect approximately account observed EM variations during earthquake ground motions [e.g. Gao et al. 2016, GRL]. However, there are still considerable disagreement between observed and calculated EM variations.

In the present work, I have derived a formula to calculate EM variations arising from motional indcution effect. An analytical expression of this kind of EM variation for a full-space medium has already derived by Gao et al. [2014, JGR], but that for half-space media have not been derived. I derived the required expression by means of a well-established method in seismology to consider stratified media [see, for example, a textbook by Kennet, 2013].

I am now planning to compare the resultant expression to a previously derived full-space solution. To confirm whether the motional effect explains the previously unexplained EM variations is the next work.

地震動は、さまざまなメカニズムを通じて電磁場変動を生成する。考えうるメカニズムには、界面導電現象、動的電磁誘導、ピエゾ電気・磁気などがある。その各々について、そこから生成される電磁場変動の計算方法が考察されている。現在、主要なメカニズムだと考えられているのは界面導電現象である。たとえば、パークフィールド地震時に観測された電磁場変動のかなりの部分が界面導電現象で説明できたとする報告がある [例えば Gao et al. 2016, GRL]。しかし、観測値と計算値の間には依然として小さくない不一致が含まれており、その他のメカニズムの寄与も無視できないと考えられる。

本研究では、動的電磁誘導により成層媒質中に生成される電磁場変動の表現式を導出した。無限媒質中の電磁場変動の表現式は、すでに Gao et al. [2014] が導出しているが、地表の効果を正しくとりいれた成層媒質中の解は求められていない。今回、解を求めるために、成層弾性媒質中の地震波伝搬を記述するために地震学で用いられる方法 [参考：Kennet, 2013] を援用して、所要の解を導出した。

今後、得られた解を、無限媒質中を仮定した場合の解 [Gao et al. 2014, JGR] と比較する。そして、これが具体的な観測事例を説明するのかについて検証する予定である。

霧島硫黄山でとらえられた2016年熊本地震活動に伴う電磁気シグナルについての第1報

上嶋 誠 [1]; 相澤 広記 [2]; 塚本 果織 [3]; 神田 径 [4]; 関 香織 [5]; 木下 貴裕 [5]; 大湊 隆雄 [1]; 渡邉 篤志 [1]
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The first report of coseismic EM signals in the 2017 Kumamoto Earthquake Sequences by the Iwo-yama MT campaign

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Coseismic EM signals associated with large inland earthquakes were often detected and reported in the previous studies. The mechanism for generating those signals, however, have not been understood clearly, although several mechanisms were proposed in terms of piezo-electricity, piezo-magnetism, motional-induction or electrokinetic effect. In order to clarify the mechanism, it is desirable to catch the signal at not a small number of stations and to investigate characteristics in spatiotemporal distribution of the signals, with seismic recordings nearby the EM sites. However, due to rare occurrence of the inland earthquakes, such observations were rarely reported in the previous literatures especially for the main shocks.

In Iwo-yama area in the Kirishima volcanic group, in Kyushu, SW Japan, we performed an MT survey to investigate recent volcanic activities (inflation of the volcanic body, activation in the volcanic gas eruptions and development of the thermal anomaly). We put 7 ADUs (Metronix, Ex, Ey, Hx, Hy, Hz) and 20 ELOGs (NT System Design, only Ex, Ey) around the Iwo-yama volcano and measurements at all the stations started from day time (in JST) on April, 14, 2016. We recorded EM time series of 32 Hz from 0:00 to 23:50UT and that of 1024Hz from 17:00 to 18:00UT, every day. After then, the foreshock and the main shock of the Kumamoto earthquake occurred respectively at 21:26 JST on April 14 and 01:25 JST on April 16. EM signals cause. The data were acquired until day time (in JST) of April 28 at all the stations except 2 stations. Thus, we could get EM signals associated with the seismic waves propagated from the Kumamoto earthquake focal areas.

There also exists continuous seismic stations operated by ERI, JMA and NIED in the area. Among all, the station KAR by ERI was located very close to one of the E stations and we could directly compare the time series of EM and seismic signals for almost all the main earthquakes occurred in the 2016 Kumamoto Earthquake sequences. In this presentation, we will show basic characteristics of both of the pre-wave and co-wave EM signals and comparison with the seismic records.

GAIA Sq ソースモデルによるグローバル電磁誘導計算とマントル電気伝導度構造推定への応用

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Global induction modeling by the GAIA Sq model and its application toestimation of the electrical conductivity in the mantle

Takao Koyama[1]; Yuka Murata[2]; Shigeru Fujita[3]; Ikuko Fujii[4]; Kiyoshi Baba[5]; Yasunobu Miyoshi[6]; Hitoshi Fujiwara[7]; Hidekatsu Jin[8]; Hiroyuki Shinagawa[8]
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The electromagnetic sounding has been widely used to reveal the electrical conductivity structure in the Earth. For shorter periods than 10000 sec, a plain wave approximation of the EM field may be valid and generally used in magnetotelluric method to elucidate the structure of subsurface, crust and uppermost mantle. For longer periods than several days, a simple P10 distribution approximates well the EM variations in global scale and can reveal the structure in a lower part of the mantle transition zone and lower mantle. In order to unveil the whole mantle structure, intermediate bands are inevitable. The geomagnetic field in this band such as Sq field, however, is known to have complicated distributions and careful consideration of a spatial distribution of the EM variation must be required. On the other hand, geomagnetic observatories are sparsely and unevenly distributed on the ground, and thus it is difficult to detect a realistic Sq field distribution from only the on-land geomagnetic observatory data.

In our paper, instead of conventional ways, we use the GAIA (Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy) model to represent a realistic Sq field (e.g. Jin et al. 2011, Miyoshi et al. 2011). The GAIA model is a whole atmosphere model from the surface to the exobase including the ion and electron dynamics and the dynamo process in the ionosphere. It is noted that the GAIA model employed for the Sq calculation assimilates the meteorological reanalysis data (JRA-55) to the whole atmosphere-ionosphere coupled model. Therefore, it provides us 3-D grid point values of the realistic electrical current in ionosphere.

By using the Sq model derived from the GAIA and a supposed conductivity model in the Earth, the effect of the global induction is evaluated to compare the geomagnetic field data on the ground. We choose some quiet days in each season from time series of the GAIA model and performed numerical induction modeling in a frequency domain by using the 3-D CIE numerical code (Koyama et al. 2014). The conductivity structure in the Earth is supposed to be a layered structure with a horizontally heterogeneous structure of ocean-land contrast on the top.

As the results, we found that the vertical magnetic component is reduced by about 50% and the horizontal magnetic components are enhanced by 30%. We also found that some phase delays occur due to highly conductive ocean, and they sometimes explain the observed geomagnetic data better. We should note, however, that the focus of the Sq field is mislocated and thus discrepansy of north-south component between observed and numerical data is large. Then we conducted synthetic test of 3-D inversion of the electrical conductivity in the Earth by using Sq model and concluded that it is very sensitive to the mantle structure in 200-400 km depth.

In our presentation, we show the forward results of the induction modeling due to the GAIA Sq source and compare the observed and numerical data. Also we will show a potential to use the GAIA model as the Sq source field to elucidate the electrical conductivity in the Earth’s mantle.

従来地下の電気伝導度構造を推定する際に、外部電磁場ソースは 10,000 秒よりも短周期側を使用する場合は平面波でよく近似でき、また、数日よりも長周期側では地磁気座標系における P10 のダイポールソース、つまり地磁気軸方向を向く一様な磁場でよく近似できることが知られており、これら非常にシンプルなソース形状の仮定のもとでもっぱら電気伝導度構造解析に使用されている。

一方で、およそ 10,000 秒から 100,000 秒の帯域は電離層起源の Sq 場が存在することが知られている。Sq 場の空間波長を仮に平面波として近似してしまうと磁場データは有意にずれるため、特に Sq 場が卓越する場合の地磁気静穏日データを解析する際には、Sq 場の空間分布を適切に考慮した解析方法が求められる (e.g. Shimizu et al. 2011)。Sq 場の空間分布を知るためには、多点での観測が必要であるが、陸上の定常磁場観測点は世界でも 100ヶ所程度と数が少なく、また、分布も陸域に、かつ、陸域でも特定の地域に偏っており、既存の陸上データのみから適切な Sq 場の分布を知ることは困難である。

そこで、本研究では Sq 場を磁場の観測データから求めるのではなく、まったく別の物理・化学を基にした「GAIA モデル」を利用することとした (e.g. Jin et al. 2011, Miyoshi et al. 2011)。GAIA モデルは下層大気から超高層大気までの大気圏モデルおよび電離圏モデルのカップリングを考慮し、電磁流体力学や光化学反応系などを満たすように統合解析されており、表層での気象データ (JRA-55 再解析データ) の同化もなされているモデルである。この GAIA モデルによる電

離層電流系が作る磁場分布 (村田 2017) を外部ソースとして用いて、地下の電気伝導度構造による電磁誘導の効果を計算し、実際に地磁気観測点で測定された磁場値との比較をおこなった。

最初のテストとして、地下の構造としては単純な水平成層構造に加え、最上部表層にのみ海陸および堆積層等による水平不均質があるという電気伝導度モデルを用いた。電磁誘導の計算には CIE 法（e.g. Singer et al. 1995, Pankratov et al. 1995）によるグローバル３次元計算コード（Koyama et al. 2014）を使用した。Sq 場は太陽との位置関係からその分布に年周変動があるため、ここでは、夏・秋（分）・冬の３期の静穏日について計算し、データとの比較をおこなった。

おおまかな傾向として、外部ソースの磁場と地下構造による誘導を加味した磁場とでは、鉛直成分がおよそ 1/2 に減少し、水平成分はおよそ 1/3 増加することがわかり、データとの一致も比較的によいことがわかった。また、表層不均質の影響により、特に海の影響による位相の遅延をよく説明できることも示された。特に海と陸の境界でのイレギュラーな時間変化が顕著であり、日本のような海と大陸の境界付近の磁場観測値を使う場合はこの点に注意が必要であることが示唆される。磁場データとの比較で悪かった点しては、Sq 場の極大点、いわゆる「目玉」、の緯度が現実とモデルとはずれがあり、特に磁場の南北成分での Sq 場極大点付近における不一致が顕著に見てとれる。そのため、季節によってデータとの一致・不一致の度合いが変わるので、今後構造解析に用いる場合は適切な地点・時期を選択する必要がある。

また本研究では、Sq 場を用いた電気伝導度構造インバージョンコードを開発しており、それを使って GAIA モデルを入力とした構造解析を試みる。テストモデルによる感度計算では深さ 200km-400km に感度が高く、スラブ・マントルダイナミクスに重要な上部マントル下部から遷移層にかけての構造を明らかにすることができる。

本発表では、GAIA モデルを外部入力した場合の電磁誘導の効果および実際の磁場データとの比較と、それを利用した地下電気伝導度構造推定の可能性について発表・議論する。

Nation-wide deep electrical conductivity structure in the China Mainland

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This presentation gives a description of very deep electrical conductivity structure beneath mainland China by using geomagnetic depth sounding (GDS). We have obtained the C-responses at 42 observatories in the mainland China in the period range from 1.3d to 113.8d. The hourly data of the 3 component magnetic field (1995-2016) were retrieved from the National Geomagnetic Network Center (GNC). Both the Occam 1-D inversion and rho+ 1-D inversion were applied to the C-responses. We examined whether the 1-D assumption at each station is denied or not by evaluating RMS values. Except LSA (Lasa) whose RMS slightly exceed the acceptable RMS and the observatories near the coast, all of the other observatories passed the rho+ 1-D inversion check. The resulting conductivity model was compared with the previous work. We found that the mantle transition zone has a large gradient of conductivity, resulting in a relatively high value about 0.3S·m-1 at the depth of 660km beneath northeastern part of China, which is more conductive than those of other tectonic settings by at least one order magnitude. In the North China, it shows obviously the different characteristics among the Ordos block, western part and the gravitational gradient zone along Daxinganling Mountain-Taihang Mountain, which is correspond to the differences in thickness and stability of lithosphere. This feather may be due to the subduction of India plate from the southwest and Pacific Plate from the east. We will also try to evaluate the ocean effect on the C-response to get a more realistic electrical conductivity model of deep structure of mainland China.

R003-P09 **会場: Poster** **時間: 10月17日**

紀伊半島のMT法による3次元構造解析 (2)

木下 雄介 [1]; 小川 康雄 [2]; 齋藤 全史郎 [3]; 野口 里奈 [4]; 市來 雅啓 [5]; 山口 覚 [6]; 藤田 清士 [7]; 梅田 浩司 [8]; 浅森 浩一 [9]
[1] 東工大・理・地惑; [2] 東工大・火山流体; [3] 東工大・地惑; [4] 東工大・火山流体; [5] 東北大・院理・地震噴火予知センター; [6] 大阪市大院・理・地球; [7] 阪大・工; [8] 弘前大・理・地球環境; [9] 核燃料サイクル開発機構

Three-dimensional magnetotelluric imaging of Kii peninsula (2)

Yusuke Kinoshita[1]; Yasuo Ogawa[2]; Zenshiro Saito[3]; Rina Noguchi[4]; Masahiro Ichiki[5]; Satoru Yamaguchi[6]; Kiyoshi Fujita[7]; Koji Umeda[8]; Koichi Asamori[9]
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Although Kii peninsula is located in the forearm side of southwest Japan, it has high temperature hot springs and fluids from mantle are inferred from the isotopic ratio of helium. Non-volcanic tremors underneath the Kii Peninsula suggest rising fluids from slab.

Previously, in the southern part of the Kii Peninsula, wide band magnetotelluric measurements were carried out (Fuji-ta et al.,1997; Umeda et al.,2004). These studies could image the existence of the conductivity anomaly in the shallow crust and in the deep crust. Long period observation using network MT data showed low resistivity on wedge mantle (Yamaguchi et al.,2009). These studies, however, used two dimensional inversions and three-dimensionality is not fully taken into consideration.

As part of the "Crustal Dynamics" project, we have measured 20 more stations so that the whole wide-band MT stations constitute grids to make three-dimensional modeling of the area.

In total we have wide-band magnetotelluric sites. Preliminary 3d inverse modeling showed the following features.

(1) The high resistivity in the eastern Kii peninsula at depths of 5-40km. This may imply consolidated magma body of Kumano Acidic rocks underlain by resistive Philippine Sea Plate which subducts with a low dip angle.

(2) The northwestern part of Kii Peninsula has the shallow low resistivity in the upper crust.

(3) The northwestern part of the survey area has a deeper conductor in the lower crust to upper mantle. This reflects the Philippine Sea subduction with higher dip angle.

2016 年熊本地震周辺域の比抵抗構造

2016 年熊本地震比抵抗構造研究グループ 相澤　広記 [1]
[1] -

Three dimensional resistivity structure around the rupture zone of the 2016 Kumamoto earthquake

Aizawa Koki Research Group for the resistivity structure around the regions of the 2016 Kumamoto earthquakes[1]
[1] -

Three dimensional inversion of magnetotelluric (MT) data around the focal region of Mw 7.0 Kumamoto earthquake were conducted. Previous MT data (Asaue et al., 2004; Asaue et al., 2007; Asaue et al., 2012) and new MT and telluric data with good data quality were used for the inversion. Total number of sites are seventy-nine. We inverted the full impedance tensor (four complex components: Zxx, Zxy, Zyx, and Zyy) and geomagnetic transfer functions (two complex components: Tx and Ty) by using the code developed by Siripunvaraporn and Egbert (2009). The horizontal mesh size was set to 2000 m in the area around the observation sites and was logarithmically increased with increasing distance from the focal are the Kumamoto earthquake. The model also takes into account the features of topography and bathymetry.

The preliminary result shows two dominant conductive bodies that are located (1) slightly east of the hypocenter of main shock and (2) beneath Aso volcano. The rupture areas of the mainshock (Asano and Iwata, 2016) are sandwiched by the two conductive bodies. We will investigate the spatial correlation to the foreshock migration (Kato et al., 2016) before the Kumamoto earthquake.

Magnetotelluric Transect of The Unzen Graben

Agnis Triahadini[1]; Koki Aizawa[2]; Dan Muramatsu[3]; Kaori Tsukamoto[3]; Keita Chiba[4]; Saki Watanabe[3]; Yui Odasaki[4]; Yoshiko Teguri[4]
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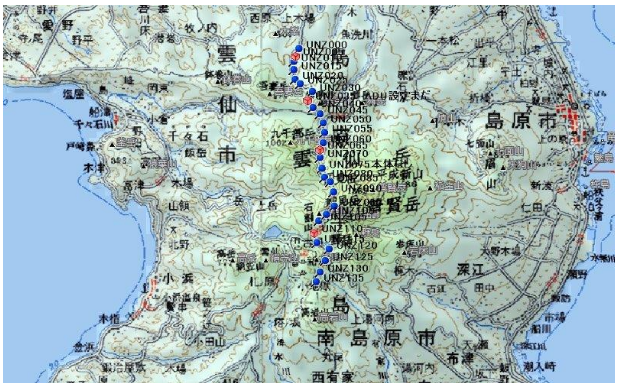
Magnetotelluric (MT) method has been employed in the western side, 2 km away, of the summit of Unzen Volcano. Unzen is grown within the East-West (E-W) trending graben structure, resulting many nornal faults. We accomplished the measurement by aligning North-South (N-S) trending line crossing the graben structure . We installed 28 MT stations spatially distributed every 300-400 meters, consisted of 4 five-components MT stations and 24 two-components telluric stations. A seismic survey reflection survey was carried out along the same survey line (Matsumoto et al., 2012). Furthermore, we are interested in comparing the resistivity structure with seismic profile to interpret the faults and more importantly the possibly magma conduit of 1991-1995 eruption that assumed exists beneath survey line. Many research suggests the magma rose obliquely in E-W, from below Tachibana Bay in the west offset to the summit of volcano through the inclined conduit. Thus, we calculated impedances and geomagnetic transfer functions by remote reference processsing using a reference stations located in Kirishima Volcanoes. Consecutively, we will show the preliminary result of resistivity structure beneath this profile.



Synthetic three-dimensional finite-element electromagnetic modelling study of Nishinoshima magma chamber.

Anna Avdeeva[1]; Kiyoshi Baba[2]; Takao Koyama[3]
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Most of the currently used electromagnetic (EM) modelling and inversion codes approximate earth subsurface with rectilinear structured meshes. This is not optimal, especially in a marine environment, as a large portion of the computationally feasible grid is used up by bathymetry, at the same time reducing the resolution of the upper region. We implement an efficient, flexible and robust EM modelling code, that is based on finite-element (FE) methods with adaptive unstructured meshes and allows accurate approximation of complex model geometries. Finite-element modelling approaches only recently started to become popular in the EM community. At the same time, FE methods have been used extensively in other fields, in particular in solid mechanics and fluid dynamics, and are the focus of active mathematical research. We transfer the FE experience gained in other fields to geophysics. Our code uses the open source FE library *deal.II*. This library is based on fully unstructured hexahedral meshes which typically require 4-10 times fewer elements than tetrahedral meshes to obtain the same rate of convergence. In addition, *deal.II* allows for a high level of parallelization and scales to several thousand processors.

We show first results of the application of the code for imaging the newly developed volcanic island Nishinoshima. Imaging of Nishinoshima's magma chamber will help to understand the processes that are involved in the development of new continental crust. Nishinoshima is located in an area with complex sea-floor bathymetry which has to be properly incorporated into resistivity models in order to obtain accurate EM responses, as otherwise the responses on the slopes of the bathymetry can differ by orders of magnitude.

In the future, and outside of the scope of this work, we will employ the newly-developed FE forward code as an engine for an inversion. We plan to invert the data acquired at the Nishinoshima island that were retrieved from the sea-floor end of May this year, to image the magma chamber.

四国西部上部地殻の空隙特性

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The properties of pores in the upper crust of the western part of Shikoku region estimated by electric resistivity and gravity

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We estimated the properties of pores in the upper crust of the western part of Shikoku region by electric resistivity and gravity data. The low electric resistivity regions of less than 10ohm-m in the upper crust of the western part of Shikoku have been reported. The electric resistivity of the crust is a function of rock resistivity, porosity, pore fluid resistivity, aspect ratio of pore, and connectivity of pores. In particular, the resistivity depends on the properties of pores and the resistivity value of pore fluid. The properties of pores are often estimated using seismic tomography data. In this study, we estimated the porosity of the upper crust of the western part of Shikoku by the Bouguer gravity anomaly data. In the western part of Shikoku, low Bouguer gravity anomaly regions and low resistivity regions correspond to each other. We analyzed the low Bouguer gravity anomalies on the assumption that they are caused by low density pore fluid. In this case, the obtained porosity is independent of pore aspect ratio and pore connectivity. We report the properties of pores in the upper crust of the western part of Shikoku that can explain the observed low electric resistivity value.

地殻内の空隙の状態を推定する方法には，弾性波，比抵抗，重力データを用いる方法がある。弾性波，比抵抗による推定では空隙の形状・連結度を仮定する必要があるが，重力による推定では，空隙の形状・連結度を仮定することなく空隙の体積分率を推定することが可能である。本研究では，鳥取大学（2009），山下・小原（2010）が行った四国西部における広帯域 MT 法比抵抗探査の測線に沿って，比抵抗と重力のデータを使い上部地殻の空隙の特性について推定をおこなった。

鳥取大学 (2009)，山下・小原 (2010) では，測線の位置は異なるものの四国西部域の上部地殻に仏像構造線付近を境界として南北 2ヶ所に 10ohm-m 以下の低比抵抗領域が存在することを報告している。また，山下・小原 (2010) は Matsubara et al.(2008) の地震波トモグラフィーの結果に武井 (2005) の方法を適用して空隙率及び空隙の形状・連結度を推定し，これら低比抵抗の原因が CO_2 及び NaCl 等の塩を含む間隙流体であるとしている。

四国西部域の低比抵抗領域の広がりとブーゲ異常の負異常の分布と相関がよいことから，ブーゲ異常データから空隙の形状・連結度を仮定することなく空隙率を求めた。公表されているブーゲ異常図に，プレートの影響を除くために何種類かのハイパスフィルタをかけた結果，カットオフ 50km のハイパス・フィルタをかけたものがもっとも相関が高いと判断された。比抵抗測線に沿って得られたブーゲ異常を説明する密度構造を 2 次元タルワニ法にて推定し，低密度の原因が低密度の間隙流体の存在と仮定して空隙率（0.01-0.04）を推定した。ここで推定する空隙率は，空隙形状や空隙の連結度とは独立である。

次に，渡辺（2005）の固相ー液相共存モデルを使用し，空隙の形状・連結度の範囲について比抵抗値との比較により検討した。その結果，アスペクト比は 0.01-0.04 程度, 連結度は 0.4-0.9 程度という結果が得られた。これらは，山下・小原 (2010) の結果とおおよそ一致しているがやや大きい傾向にある。

謝辞：解析に使用したブーゲ異常図は，愛媛大学の山本明彦教授より提供を受けました。ここに感謝申しあげます。