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MGI032-01 会場:102 時間:5 月 23 日 16:30-16:45

グリーン関数の不確定性を考慮した震源過程の波形インバージョン解析
Introduction of uncertainty of Green's function into waveform inversion for seismic source processes

八木 勇治[1*], 深畑 幸俊[2]
Yuji Yagi[1*], Yukitoshi Fukahata[2]

[1] 筑波大学大学院生命環境科学研究科, [2] 京都大学防災研究所
[1]University of Tsukuba, [2]DPRI, Kyoto University

我々は地球の真の速度構造を求めることはできず、観測波形と震源過程を結びつけるグリーン関数の真の値を求めることはできない。このグリーン関数の不確定性は、震源波形インバージョンにおいて最も大きな誤差項であると考えられている。この誤差項を小さくするために、３次元速度構造を仮定してグリーン関数を計算する、または、中小地震の観測波形を経験的グリーン関数として解析に利用する等の研究が行われてきが、グリーン関数の不確定を前提とした定式化は行われてこなかった。本研究では、モデルが不完全であることを前提とした定式化を用いて、震源モデルと速度構造モデルが不完全であることを前提とした震源波形インバージョンの定式化を行った。そして、その効果を検討するために、グリーン関数の誤差の影響を強く受けていると考えられる 2006 年ジャワ津波地震に適用してその有効性を確認した。解析には，遠地実体波波形を使用し，観測誤差とグリーン関数の誤差に由来するモデリング誤差の二つの項を顧慮した定式化を行った。二つの誤差項の相対的な重み，スムージング等の拘束条件との相対的な重みは ABIC を用いて推定した．まず、単純な震源モデルを仮定して、すべり速度関数にガウシアンノイズを、計算したグリーン関数のガウシアンノイズを加えて合成波形を計算し、これを観測波形として解析を行った。この数値実験の結果、従来の定式化では、仮定したすべり方向と逆方向の大きなすべりが得られ、解が不安定になるのに対して、本研究の定式化では、仮定した震源過程と同様の解が得られた。次に、実際に観測された地震波形に適応して解析を行った結果、従来の定式化では、スムージングはより強い値が選択されているのにかかわらず CMT 解と矛盾するすべりベクトルを含む複雑なすべり量分布が得られるのに対して、新しい定式化では、CMT 解と調和的なすべり量分布が得られた。従来の定式化では、スムージングが強くなるために、波形の高周波成分が再現できないが、新しい定式化では、高周波成分も良く再現することができている。これらの結果は、従来の研究では無視されてきたモデリング誤差を適切に扱う重要性を示している。

キーワード: 震源過程, 波形インバージョン, グリーン関数の不確定性, モデリング誤差, 津波地震
Keywords: Seismic Source Process, Waveform Inversion, Uncertainty of Green's function, Modeling error, Tsunami Earthquake

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MGI032-02 会場:102 時間:5 月 23 日 16:45-17:00

地震波・地震音波データ同化による 2008 年岩手・宮城内陸地震の断層パラメータ推定
Fault parameters inferred from data assimilation on seismic & acoustic waves due to 2008 Iwate-Miyagi Nairiku Earthquake

長尾 大道 [1*], 中野 慎也 [1], 樋口 知之 [1]
Hiromichi Nagao[1*], Shin'ya Nakano[1], Tomoyuki Higuchi[1]

[1] 統計数理研究所
[1]The Institute of Statistical Mathematics

An evidence of seismoacoustic waves due to a big earthquake is sometimes recorded in barometer data at an infrasound observatory several hundred kilometers away from the hypocenter. Such infrasound variations must contain information of the source mechanism of the earthquake and structures of both solid Earth and atmosphere. Therefore it is possible to obtain, from a different perspective from seismic data, knowledge about earthquakes by analyzing the infrasound data.

Here we estimated the fault parameters of the 2008 Iwate-Miyagi Nariku Earthquake carrying out data assimilation on infrasound data. First we calculated a set of eigenfunctions of normal modes (Kobayashi [2007]) related to a one-dimensional coupled model consisting of the solid Earth (PREM; Dziewonski and Anderson [1981]) and the atmosphere (NRLMSISE-00; Picone et al. [2002]). Then we constructed prior distributions for the fault parameters such as rupture length and velocity by integrating models previously proposed from many universities and institutes. Finally we applied a sequential Monte Carlo (SMC) method such as the particle filter algorithm to a combination of simulated waves derived from the eigenfunctions and observed data obtained at CTBTO Isumi microbarometer array. We will discuss especially on the obtained posterior distributions of the fault parameters and differences between our result and the previous ones.

キーワード: データ同化, ベイジアンフィルタ, 粒子フィルタ, 微気圧, 地震音波, 岩手・宮城内陸地震
Keywords: data assimilation, Bayesian filter, particle filter, infrasound, seismoacoustic wave, Iwate-Miyagi Nairiku Earthquake

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MGI032-03 会場:102 時間:5 月 23 日 17:00-17:15

地下水流動シミュレーションにおける粒子フィルタを用いた透水係数の同定
Identification of hydraulic conductivity of groundwater flow simulaiton using a particle filter

山本 真哉 [1*], 本多 眞 [1]
Shinya Yamamoto[1*], Makoto Honda[1]

[1] 清水建設株式会社
[1]Shimizu Corpolation

浸透流解析では透水係数などのパラメータを適切に設定することが重要となる。しかし、これらのパラメータは計測のサンプル数が不十分であったり、原位置での計測自体が困難であったりするために実際の値を知ることは難しく、その設定には経験や技術を要する。さらに、設定すべきパラメータが多数あるような解析ケースでは、観測結果を十分に再現できるシミュレーションを得るのに大きな困難を伴うことが多い。

本研究は観測データの活用という観点に立ち、逐次データ同化の一手法である粒子フィルタを地下水流動シミュレーションに適用して透水パラメータを同定することでシミュレーションモデルの高精度化を目指すものである。

データ同化の精度検証を行うために、フィルダムを対象として 2 次元飽和・不飽和浸透流シミュレーションによる数値実験を実施した。本研究では観測データを堤体および基礎部の漏水量とし、あらかじめ真値を設定した透水係数を用いて順解析を実施し、これから算出された漏水量の値を模擬的な観測データとした。この漏水量データと浸透流シミュレーションモデルとの逐次データ同化を行った結果、遮水ゾーンや基礎岩盤の透水係数を精度良く同定することが可能であった。また、状態変数の事後分布から各部の透水係数が漏水量の観測値に与える影響を評価できた。

本手法はダムの維持管理において、遮水性能に変化が生じた場合の変状箇所の同定にも応用できると考えられる。

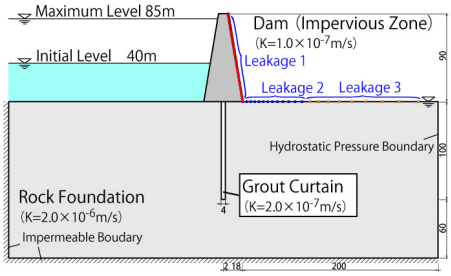

Fig1. Analytical model

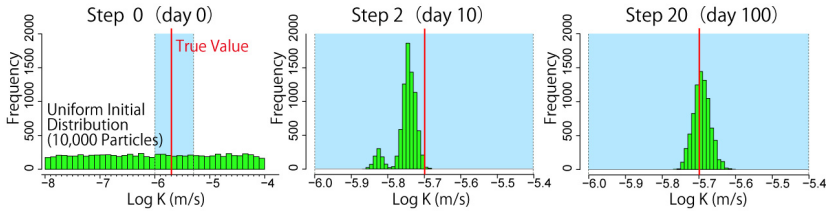

Fig2. Change of particle distribution of the hydraulic conductivity (rock foundation)

キーワード: データ同化, 粒子フィルタ, 地下水流動シミュレーション
Keywords: data assimilation, particle filter, groundwater flow simulation

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MGI032-04 会場:102 時間:5 月 23 日 17:15-17:30

粒子フィルタのプラズマ圏データ同化への応用
Application of the particle filter to data assimilation for a plasmasphere model

中野 慎也 [1*], Fok Mei-Ching[2], C:son Brandt Pontus[3], 樋口 知之 [1]
Shin'ya Nakano[1*], Mei-Ching Fok[2], Pontus C:son Brandt[3], Tomoyuki Higuchi[1]

[1] 統計数理研究所, [2]NASA Goddard Space Flight Center, [3]JHU/APL
[1]The Institute of Statistical Mathematics, [2]NASA Goddard Space Flight Center, [3]JHU/APL

The particle filter (PF) is an algorithm applicable to general data assimilation problems including non-linear and non-Gaussian problems. Since the PF is suitable for parallel computing, it is considered to be one of promising algorithms for data assimilation problems with high nonlinearity. In this study, we applied the PF to data assimilation for the Earth's plasmasphere. The plasmasphere is the innermost region in the magnetosphere filled with cold dense plasma. We describe the technical aspect of our data assimilation method and show results of applying this data assimilation technique to the plasmasphere.

キーワード: 粒子フィルタ, データ同化, プラズマ圏
Keywords: particle filter, data assimilation, plasmasphere

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MGI032-05 会場:102 時間:5 月 23 日 17:30-17:45

地上磁場と GPS TEC の同時観測データを用いるプラズマ圏密度分布推定手法
Method for estimating the plasmaspheric density distribution from the ground magnetic field and GPS TEC

河野 英昭 [1*], 才田 聡子 [2], 上野 玄太 [3], 樋口 知之 [3], 中野 慎也 [3], 湯元 清文 [4]
Hideaki Kawano[1*], Satoko Saita[2], Genta Ueno[3], Tomoyuki Higuchi[3], Shin'ya Nakano[3], Kiyohumi Yumoto[4]

[1] 九州大学大学院理学研究院地球惑星科学部門, [2] 情報・システム機構新領域融合研究センター, [3] 情報・システム研究機構統計数理研究所, [4] 九州大学 宙空環境研究センター
[1]Kyushu University, [2]Transdis. Res. Integr. Center, [3]The Institute of Statistical Mathematics, [4]Kyushu University

The plasmasphere is the region in space, close to the Earth. It is a part of the magnetosphere (region filled with the Earth-origin magnetic field). The plasmasphere is filled with ionosphere-origin plasma, and the shape of the plasmasphere changes in response to the activity of the magnetosphere. It is important to monitor three-dimensional plasma distribution in and near the plasmasphere; for example, the plasmasphere can affect the progress of magnetic storms via plasmasphere-ring current interactions (the ring current is another region in which strong electric currents, carried by plasma there, flow in the shape of a ring surrounding the Earth).

Measures to monitor the three-dimensional density distribution in and near the plasmasphere includes ground magnetometers and GPS satellites, as follows. From ground magnetometer data one can identify the eigenfrequency of the field line running through the magnetometer. From thus identified frequency (so-called FLR frequency, where FLR stands for "field line resonance"), one can guess the plasma mass density distribution along the field line. Ground coverage by magnetometers is getting thicker day by day toward two-dimensional ground coverage, from which one can guess three-dimensional plasma density in the region threaded by the field lines running through the ground surface.

Each GPS satellite provides TEC (total electron contents) along the line of sight from the satellite to a ground GPS receiver; from the TEC one can guess the electron density distribution along the line of sight. There are 24 GPS satellites, and the ground coverage by GPS receivers is getting thicker day by day, from which one can guess three-dimensional electron plasma density in the region covered by the line of sights from the GPS satellites to the ground GPS receivers.

In this paper we invent a method to evaluate the ground-magnetometer information and the GPS-TEC information at the same time and obtain a unified plasmaspheric plasma density distribution. In essence, the method calculates the differences between the observations and the corresponding quantities calculated from the estimated plasma distribution, and minimizes the sum of the differences for the two types of observations. Details will be given at the presentation. We first realize this method in an iterative manner by using the quasi-Newton method. We have so far tested it with simulated data; we will show the results at the meeting. Further tests with sample data are ongoing.

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MGI032-06 会場:102 時間:5 月 23 日 17:45-18:00

アジョイント法による余効すべり時空間発展の予測手法の開発
Development of Forecasting Method of Spatio-Temporal Afterslip Evolution by Adjoint Method

加納 将行 [1*], 宮崎 真一 [1], 伊藤 耕介 [1], 平原 和朗 [1]
Masayuki Kano[1*], Shin'ichi Miyazaki[1], Kosuke Ito[1], Kazuro Hirahara[1]

[1] 京都大学理学研究科地球惑星科学専攻
[1]Geophysics, Kyoto Univ.

We develop a method to forecast spatio-temporal afterslip evolution based on adjoint method for the purpose of predicting the second event of compound earthquakes. One large earthquake sometimes triggers another earthquake nearby with the intervals of hours to years. An example includes megathrust earthquakes at the Kurile Trench. The 2004 November 29 Nemuro-oki earthquake followed the 2003 September 25 Tokachi-oki earthquake. A significant afterslip was observed between those two earthquake rupture regions. Furthermore the afterslip has propagated from the Tokachi-oki earthquake region to the Nemuro-oki region. Thus the Nemuro-oki earthquake is thought to be triggered by the afterslip. In such a case, forecast of afterslip propagation may help to predict the triggering of the second large event (the Nemuro-oki earthquake in this case).

This study is dedicated to develop a forecasting system of afterslip evolution. Evolution of slip velocity and frictional coefficient is governed by a rate- and state- dependent friction law. Three frictional parameters determine the friction that acts on the plate interface. Thus we need to know frictional parameters in addition to the initial conditions of differential equations. Kano et al. (2010, in Japanese) first employed an adjoint method and examined how this method works for our purpose by twin experiments. They used decaying phase of afterslip velocity on the plate surface to update frictional parameters. However, all frictional parameters are not constrained by those data. Thus we use data for the propagation of afterslip and investigate the possibility of estimating other parameters. The results are summarized as follows:

(1) Decaying part of afterslip data constrains the initial value of slip velocity and frictional parameter a-b, but does not either the initial value of state variable or the parameter L.

(2) Early phase of afterslip data prior to reaching to the steady state constrains the parameter L and initial value of state variable theta.

(3) Data for the propagation of afterslip constrains all of parameters a, a-b, and L.

The adjoint method, which is numerically efficient one, would be one of the future courses of developing a forecasting system of earthquake generation.

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MGI032-07 会場:102 時間:5 月 23 日 18:00-18:15

アジョイント法による地震断層面・余効すべり面摩擦パラメータの同時推定
Simultaneous estimation of frictional parameters on earthquake and afterslip rapture areas using an adjoint method

日吉 善久 [1*], 杉浦　望実 [1]
yoshihisa HIYOSHI[1*], nozomi SUGIURA[1]

[1] 海洋研究開発機構
[1]JAMSTEC

Recent developments of numerical and observational techniques in seismology and geodesy enhance our ability of drawing more realistic pictures of thrust-type earthquake generation cycles along subduction zones. Forward integrations of the equation of motion with the rate and state friction law (the frictional parameters; A, B, and L) allow to simultaneously depict the multi-time scale ruptures on a fault plane, namely, an earthquake and the associated afterslips. In addition, the denser GPS network such as the GEONET array provides more detailed information of the crustal deformation due to earthquakes. In consequence, for improving our earthquake cycle model, it is expected to assimilate the observational information on the crustal movement into the earthquake cycle model through adjusting the frictional parameters on both earthquake and afterslip surfaces.

In this couple of years, opportunities for the application of the data assimilation technique rapidly increased. However, we still face difficulties. First, few assimilation approaches are successful to simultaneously estimate all the frictional parameters on the earthquake and afterslip planes. An earthquake and the associated afterslips can be in a cause-effect sequence; therefore, their frictional parameters on both surfaces should be simultaneously obtained. However, it is difficult to simultaneously perform data assimilation of the earthquake and afterslips due to their widely-separated time constants (from a few seconds to more than a year). Second, we still make a trial-and-error method to find out an adequate assimilation time window. It is crucial to properly assess the data assimilation window for most efficiently evaluating the frictional parameters.

To tackle the first problem, we develop an adjoint backward technique with adaptive time steps based on the fifth-order Runge-Kutta forward integration (Press et al, 1993). We then apply the adjoint technique for the synthetic ”twin” experiments in which the known true model is tried to be recovered with assimilating the artificial observed data into the iterative model. The synthetic twin experiments show that our adjoint technique with adaptive time steps can estimate all the frictional parameters (A, B, and L) on the earthquake fault plane as well as the afterslip areas even in different time scales.

To find an adequate assimilation time window, we plot and analyze the sensitivities of the slip velocity (V) in terms of the parameters (A, B, and L) on the earthquake and afterslip surfaces. It suggests that the assimilation time window should cover at least that of the acceleration phase of the slip velocity ($dV/dt>0$).

We note that our results account for the possibility of estimating the frictional parameters on earthquake and afterslip surfaces in the theoretical framework. Therefore, we need to develop our adjoint method for more detailed earthquake cycle models with the real observational data.
Keywords: assimilation, adjoint method, earthquake cycle, afterslip, frictional parameter

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MGI032-08 会場:102 時間:5 月 23 日 18:15-18:30

アンサンブルフィルタにおける観測誤差共分散行列の反復推定法
An iterative algorithm for estimating the observation error covariance matrix for ensemble-based filters

上野 玄太 [1*]
Genta Ueno[1*]

[1] 統計数理研究所
[1]The Institute of Statistical Mathematics

In data assimilation, covariance matrices are introduced in order to prescribe the properties of the initial state, the system noise (model error, process noise), and the observation noise (observation error). Suitable specification of the covariance matrices is essential for obtaining sensible estimates, and misspecification of the matrices may lead to over- or under-fitting of the data and/or failure of the assimilation altogether. We present a technique for optimizing covariance matrices for observation noise.

Methods for estimating the optimal covariance are typically based on a common statistic, specifically the so-called “innovation,” which is the difference between the observation and the predicted model state. Innovations are evaluated in the methods of minimizing the squared innovations, the maximum likelihood, Bayesian estimation, and the covariance matching. The above-mentioned methods for estimating optimal covariance are, however, originally constructed based on linear-Gaussian state space models, that is, it is assumed that both the system equation and the observation equation are linear, and that both the system noise and the observation noise follows from Gaussian distributions. However, the maximum likelihood can be extended even when the system and observation equations are nonlinear (Ueno et al., 2010). Nonlinearities in the system equation are typically introduced by the advection term in the momentum equation, and can be dealt directly with by ensemble-based assimilation methods such as the ensemble Kalman filter (EnKF) and the particle filter (PF). Ueno et al. (2010) has proposed a method of ensemble-based maximum likelihood, where the likelihood is approximated with the ensemble, and demonstrated that the method can estimate the parameters that describe the covariance for system noise and observation noise. Their procedure of maximizing the likelihood, however, requires huge computational costs; it requires assimilation runs many times that amount to the total number of combinations of the parameters. It means that the method of ensemble-based maximum likelihood may not work in practice where tens or more covariance parameters need to be optimized.

Here we propose an efficient algorithm for the maximum likelihood estimation of the observation noise covariance. The algorithm is based on an analytical derivation of the derivative of the ensemble-approximated likelihood with respect to the observation noise covariance, and forms an iterative updating procedure for estimating the optimal covariance parameters. The algorithm works with the ensemble-based filters in which the likelihood can be approximated with the ensemble. Since the algorithm does not require evaluating likelihood for every combination of the covariance parameters as done in Ueno et al. (2010), it can estimate many elements in the observation noise covariance matrix.

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MGI032-P01 会場:コンベンションホール 時間:5 月 23 日 13:45-16:15

ニューラルネットワークを用いた電離圏トモグラフィーの開発
Development of Ionospheric Tomography Using Neural Network

廣岡 伸治 [1*], 服部克巳 [1], 竹田辰興 [2]
Shinji Hirooka[1*], Katsumi Hattori[1], Tatsuoki Takeda[2]

[1] 千葉大院・理, [2] 電通大
[1]Chiba Univ., [2]Univ. of Electro-Communications

電離圏で生じる様々な物理現象のダイナミクスを研究する上で、電離圏電子密度の 3 次元分布を正確に推定することは重要である。近年では GPS 掩蔽観測によって全球的な電離圏電子密度の観測も行われるようになっているが、時空間分解能の点で制約が存在する。したがって、掩蔽観測データに加え、地上 GPS 受信機観測データをベースにした電離圏トモグラフィーが電離圏ダイナミクスの研究には有効であると考えられる。

本研究では Ma et al. (2000, 2005) によって提案された Residual Minimization Training Neural Network (RMTNN) アルゴリズムに注目し、電離圏トモグラフィーアルゴリズムを開発し、その評価を行った。RMTNN は地上受信機データと、イオノゾンデによって観測される最大電子密度およびその位置データ（緯度、経度、高度）を入力とし、対象とする領域の 3 次元電子密度分布を推定する。比較的少数のデータから再構成できることが特徴である。Ma et al. (2005) は日本周辺において、シミュレーションと一部の実データについて満足できる再構成結果を得たが、電離圏擾乱時の再構成や GPS 受信機数が少ない地域についての検証は十分とはいえない。

そこで我々は本手法の再構成精度について、プラズマバブルを模した擾乱パターンと、GPS 受信機の数が制限されるスマトラ島周辺について、シミュレーションと実際の GPS データを用いて検証を行った。プラズマバブルモデルを用いたシミュレーションでは、極めて高い再構成精度が確認され、本手法の有効性が証明された。しかしながら、少数パスからの再構成では高度 250 km 以下の精度が低下する傾向が見られた。この電離圏下部の再構成精度を向上させるため、再構成領域下限 (高度 100 km) を電離圏モデル (NeQuick model) で拘束し、ニューラルネットワークの学習を実行したところ、電離圏下部だけでなく再構成領域全体の精度向上が確認された。講演では、以上の検証結果および改良点の詳細について報告する。

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GCPM と GPS-TEC を利用したプラズマ圏電子密度分布モデルの構築
A model of the plasmaspheric density profile combined with the GCPM and its error-correction model using GPS-TEC

後藤 由貴 [1*], 笠原 禎也 [1]
Yoshitaka Goto[1*], Yoshiya Kasahara[1]

[1] 金沢大学
[1]Kanazawa University

The earth's plasmasphere is filled with relatively dense core plasmas which are predominantly provided from the ionosphere. A realistic plasmaspheric density model is useful for applications not only in plasma physics but also in engineering. The plasmasphere is, however, too vast to be probed by a single spacecraft. In order to construct the realistic model, an integration of observational knowledge is indispensable. Formerly, diffusive equilibrium models were generally used to represent plasmaspheric density profiles but the models were insufficient to deal with a variety of solar and geomagnetic activities. In recent years, several new density models, such as the global core plasma model (GCPM), the global plasmasphere ionosphere density (GPID) and the standard plasmasphere ionosphere model (SIM), were developed theoretically, semi-empirically or fully-empirically. These models are more reliable than the traditional diffusive equilibrium model but each model still has weaknesses. Among these models, the GCPM has an advantage in supporting continued improvements.

The final purpose of our study is to develop a realistic plasmaspheric density model by incorporating large data sets of VLF whistler dispersions obtained by the Akebono satellite and GPS-derived TECs provided by the International GNSS Service (IGS) into the GCPM. In the present study, we adopt a new representation for the density profile. That is, the profile is constructed by a combination of the GCPM and an additional model which represents GCPM errors. The combination model makes it possible to reflect the characteristics of the long-term observations to the profile without varying the parameters in the physical base model and it always provides spatially and temporally continuous distribution. By assuming smoothness prior to the errors in multi-dimensional parameter space of the GCPM, we first estimated equatorial error distribution in order that model-derived TECs agree with the observed ones. The equatorial density is the most important factor to reconstruct the whole plasmaspheric density profile in the GCPM. By using the GPS-TECs obtained from LEO (low earth orbit) satellites, we confirmed that the developed error-reduced GCPM accurately reconstructs plasmaspheric density profiles. The model profiles show larger seasonal variations and local-time dependences than the original GCPM.

キーワード: 電子密度モデル, GCPM, GPS-TEC
Keywords: electron density model, GCPM, GPS-TEC

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地殻変動データの線形・非線形混合インバージョン： モデルパラメータとハイパーパラメータのベイズ推定
Mixed linear-nonlinear inversion of crustal deformation data: Bayesian inference of model and hyperparameters

福田 淳一 [1*], Kaj M. Johnson[2]
Jun'ichi Fukuda[1*], Kaj M. Johnson[2]

[1] 東京大学地震研究所, [2]Indiana University
[1]ERI, University of Tokyo, [2]Indiana University

We present a unified theoretical framework and solution method for probabilistic, Bayesian inversions of crustal deformation data. The inversions involve multiple data sets with unknown relative weights, model parameters that are related linearly or non-linearly through theoretic models to observations, prior information on model parameters, and regularization priors to stabilize underdetermined problems. To efficiently handle nonlinear inversions in which some of the model parameters are linearly related to the observations, this method combines both analytical least-squares solutions and a Markov chain Monte Carlo (MCMC) sampling technique. In this method, model parameters that are linearly and nonlinearly related to observations, relative weights of multiple data sets, and relative weights of prior information and regularization priors are determined in a unified Bayesian framework.

In this presentation, we define the mixed linear-nonlinear inverse problem, outline the theoretical basis for the method, provide a step-by-step algorithm for the inversion, validate the inversion method using synthetic data, and apply the method to real data sets. Our method can potentially be applied to high dimensional mixed linear-nonlinear inverse problems to which it is difficult to apply the MCMC methods to sample full posterior probability distributions due to high computational costs.

キーワード: インバージョン, マルコフ連鎖モンテカルロ法, 地殻変動
Keywords: inversion, Markov chain Monte Carlo, crustal deformation

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連続性と非線形性を考慮したアンサンブル型データ同化の精度と有効性解析
Analysis of accuracy and effectiveness in ensemble-type data assimilation considering continuity and nonlinearity

中村 和幸 [1*]
Kazuyuki Nakamura[1*]

[1] 明治大学
[1]Meiji University

データ同化においては，シミュレーションモデル内の変数が観測によって修正される．この手続きによって不確かな初期・境界条件，未知パラメータの推定や予測のより良い精度を与えることが可能となる．我々は，データ同化の中でも，アンサンブルカルマンフィルタとスムーザ，アンサンブル４ DVAR，粒子フィルタとスムーザ，融合粒子フィルタのような確率分布を直接近似できるアンサンブル型データ同化の性質に焦点を当てて解析した．まず，数理的な解析により手法間の類似と相違を比較し，その長所と短所を与える．ついで，Lorenz 96 モデルを含む複数モデルの数値解析結果を与える．これらの結果から，アンサンブル型データ同化においては，空間的連続性と非線形性が重要な役割を果たしていることが示唆される．

キーワード: データ同化, アンサンブル近似, アンサンブルカルマンフィルタ, 粒子フィルタ
Keywords: data assimilation, ensemble approximation, ensemble Kalman filter, particle filter