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MoSST_DAS: The First Generation Geomagnetic Data Assimilation Framework

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Abstract. Constraining numerical geodynamo models with surface geomagnetic observations is very important in many respects: it directly helps to improve numerical geodynamo models, and expands their geophysical applications beyond geomagnetism. A successful approach to integrate observations with numerical models is data assimilation, in which Bayesian algorithms are used to combine observational data with model outputs, so that the modified solutions can then be used as initial conditions for forecasts of future physical states. In this paper, we present the first geomagnetic data assimilation framework, which comprises the MoSST core dynamics model, a newly developed data assimilation component (based on ensemble covariance estimation and optimal interpolation), and geomagnetic field models based on paleo, archeo, historical and modern geomagnetic data. The overall architecture, mathematical formulation, numerical algorithms and computational techniques of the framework are discussed. Initial results with 100-year geomagnetic data assimilation and with synthetic data assimilation are presented to demonstrate the operation of the system.

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1 Introduction

The Earth has possessed an internal magnetic field (geomagnetic field) through much of its history. It is now widely accepted that this field is generated and maintained by convective flow in the Earth's liquid outer core (geodynamo).

Observation and study of geomagnetism can be traced far back in history. It was perhaps discovered more than 4000 years ago by Chinese [24]. While geomagnetic field properties were recorded decades earlier, one of the earliest scientific theories on the geomagnetism, *De Magnete*, was published by William Gilbert in 1600. Since then, geomagnetic studies have been developed along two separate tracks: understanding the spatial-temporal variation of the geomagnetic field (called the "kinematic track" in this paper), and understanding the origin of the geomagnetic field (called the "dynamic track"), though the latter appeared much later. In the early ages, the kinematic track was the main focus. An example is the work by Gauss on separation of internal and external magnetic fields in 1835. In this approach, the magnetic field is a potential field, and is described by a potential scalar. This scalar can then be represented by a spherical harmonic expansion and can be solved via Laplace's equation (the spectral coefficients in the expansion are called the Gauss coefficients in geomagnetism). The present work is only concerned with the internal field, so that the geomagnetic field in this paper implies only the part of the field originating in the interior of the Earth.

From surface observations it is found that the geomagnetic field varies on time scales ranging from as short as a year (e.g. geomagnetic jerks [7]), several decades (e.g. westward drift [11]), to as long as millions of years and beyond (e.g. field polarity reversal [22]). These can be described by time-varying Gauss coefficients. Combined with the spherical harmonic expansion, the geomagnetic field displays complicated spatial/temporal variation. Indeed, Gauss laid the foundation for modeling the global geomagnetic field.

In the dynamic track, dynamo theory, first proposed nearly 90 years ago [19], has been widely accepted as the most likely explanation for the origin of the geomagnetism. However, due to the complicated, nonlinear magnetohydrodynamic (MHD) processes involved, mathematical solutions (from numerical simulation) of self-consistent geodynamo action have been generated for only about the past decade. A detailed review can be found in [12].

Unfortunately, further interactions between geomagnetic field modeling and geodynamo modeling have been mainly on comparing numerical dynamo simulation results and observations, and possible geodynamic consequences [12]. There has been no attempt to combine geomagnetic field modeling and geodynamo modeling for studying the core dynamics. Perhaps the main reason is that numerical models are believed to be far from accurately simulating the real Earth's core. For example, while they display several properties similar to those of the geomagnetic field derived from surface observations, numerical model solutions cannot be labeled the "geodynamo" solutions: except the dominance of the dipole component at the core-mantle boundary (CMB), the higher