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NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

Magnetic Field Forecasting using Virtual Observatories, Core Flow Modelling and Ensemble Kalman Filtering

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Introduction and Motivation

In the last decade, accurate and detailed models of the Earth's magnetic field have been generated from the dedicated satellite missions of CHAMP, Oersted and SAC-C. Models and forecasts of the main magnetic field have valuable economic, social and logistical uses such as in resource exploration, navigation and hazard mitigation. Hence, it is important to produce the most accurate model possible for the magnetic field.

As we await the launch of the Swarm mission, there may be a gap in which our present capability is diminished. If the existing set of satellites fail before Swarm is fully operational, we may become reliant upon ground-based observatories alone to produce global magnetic field models. Due to the uneven geographic distribution of observatories these models have low spatial resolution, which is not ideal. This poster looks at potential methods for mitigating the impact of such an event by employing an optimal data assimilation algorithm to make best use of all available data.

We investigate if a sufficiently accurate forecast can be obtained using an initial high-resolution satellite field model to start with, combined with a flow model for advection of the field and intermittent updates from low resolution ground-based field model.

1) Field modelling from 'Virtual Observatories'

We first derived a set of field models from magnetic vector satellite data and used the change of the models to directly compute annual secular variation (SV). We employed the method of Mandea and Olsen (2006) to derive a 'virtual observatory' (VO) record of SV. The VO method involves binning CHAMP vector satellite data into circular bins of radius 400km placed at discrete points on a 10° x10° grid at 400km altitude above the Earth's surface.

Comparison of the SV from the 'virtual observatory' method to Niemegk and 21 other observatories gave a mean correlation of |ρ| = 0.65, 0.21, 0.73 for the dX/dt, dY/dt and dZ/dt components, respectively. Figure 1 shows the VO grid used and a comparison of SV from Niemgk (NGK).

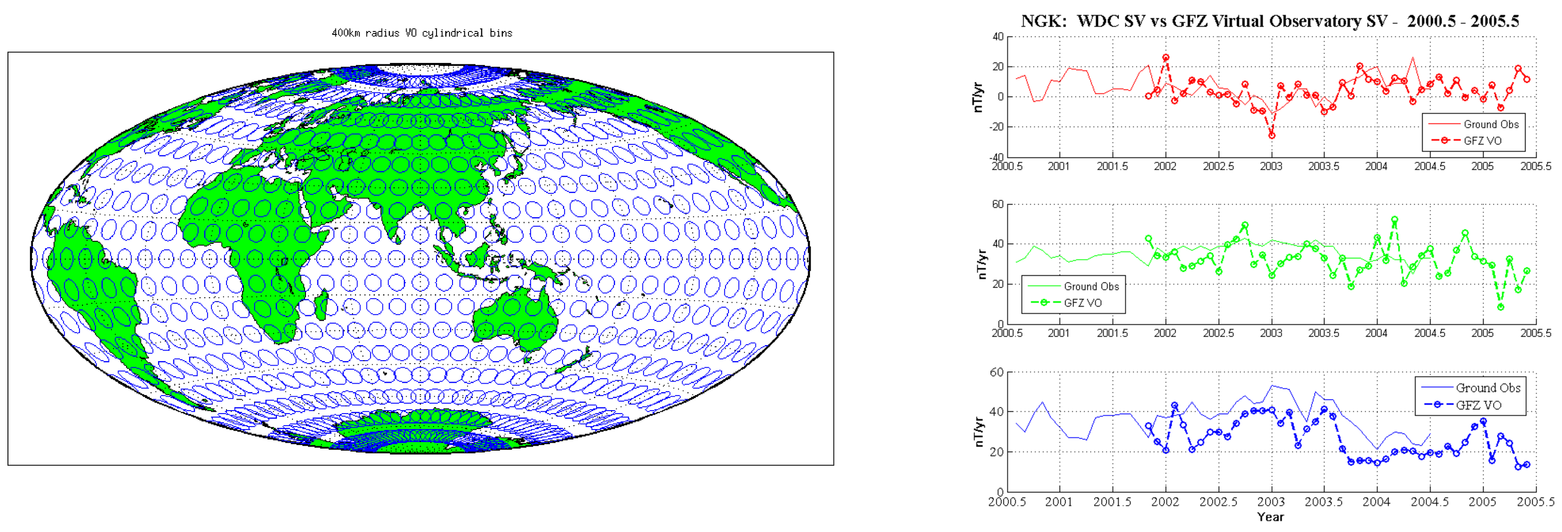


Figure 1: *Left:* The grid of Virtual Observatories used to produce a series of field models from May 2001 to June 2004. *Right:* A comparison Comparison between the SV recorded at Niemegk (Germany) and the calculated SV from a VO [θ = 37.928, φ = 12.675] at a height of 400km above the ground station in the dX/dt (red), dY/dt (green) and dZ/dt (blue) magnetic components. Note that ρ = [0.66, 0.17, 0.54].

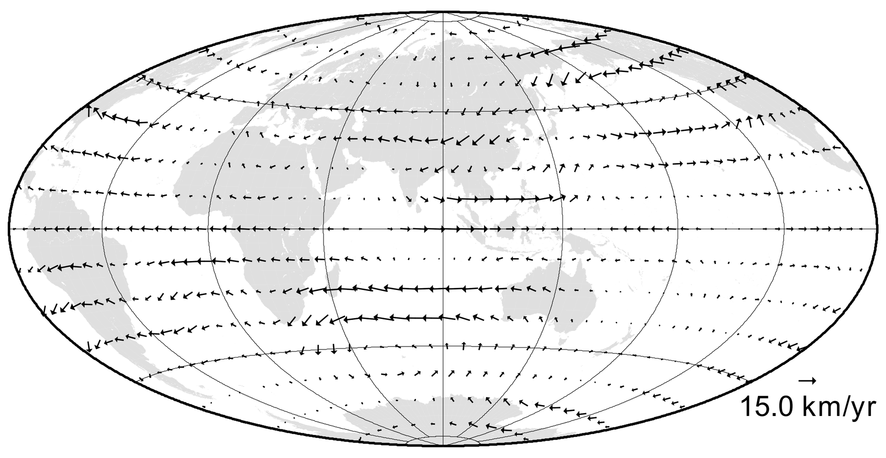
2) Producing Flow Models from VO SV

If it is assumed that the large-scale magnetic field is effectively 'frozen' into fluid outer core of the Earth over short timescales, then models of the flow along the core mantle boundary can be produced from the SV observed at the surface.

Beggan *et al.* (2009) describe a L_1 norm iterative method for directly inverting SV to infer flow along the core mantle boundary. It was also noted in their study that field models from the VO method can be biased by noise sources from external field effects (electrojets, ring current, etc).

For forecasting purposes, a steady flow model was obtained to explain the average observed SV over two years (Figure 2).

Figure 2: A steady flow model for the period 2001.91 – 2004.0, generated from VO SV using CHAMP satellite vector data. Note the flow has a tangentially geostrophic constraint applied and is damped using the Bloxham (1988) 'strong norm'. The maximum degree and order is l = 14.



3) Simple Forecasting

The steady flow model (Figure 2) was used to forecast the change of the magnetic field over the five year period from 2004.0 to 2009.0 and compared to satellite field models: GRIMM, POMME and xCHAOS.

The Gauss coefficients (g_l^m) from xCHAOS (Olsen and Mandea, 2008) for 2004.0 were used as the starting field model. The field was advected forward over successive months (k) for five years using the equation:

$$g_{k+1} = g_k + (\mathbf{H}_k \hat{m}_{SF})/12$$

where **H** is the Gaunt/Elsasser matrix (relating flow to SV) and $\hat{m}_{SF}$ are the steady flow toroidal and poloidal coefficients.

To test how well the steady flow model advects (forecasts) the field, the root-mean-square misfit ($\sqrt{dP}$) in nT was calculated (Maus *et al.*, 2008):

$$dP = \sum_{l=0}^{l=l_{max}} \sum_{m=0}^{m=l} (l+1)\left[g_{l\ field\ model}^{m} - g_{l\ forecast}^{m}\right]^2$$

Figure 3 shows the misfit of the forecast from the flow model to the GRIMM, POMME and xCHAOS satellite field models. The maximum RMS misfit is 90nT after a five year period. This compares favourably with the current misfit estimates from the IGRF10 model (~30nT/year).

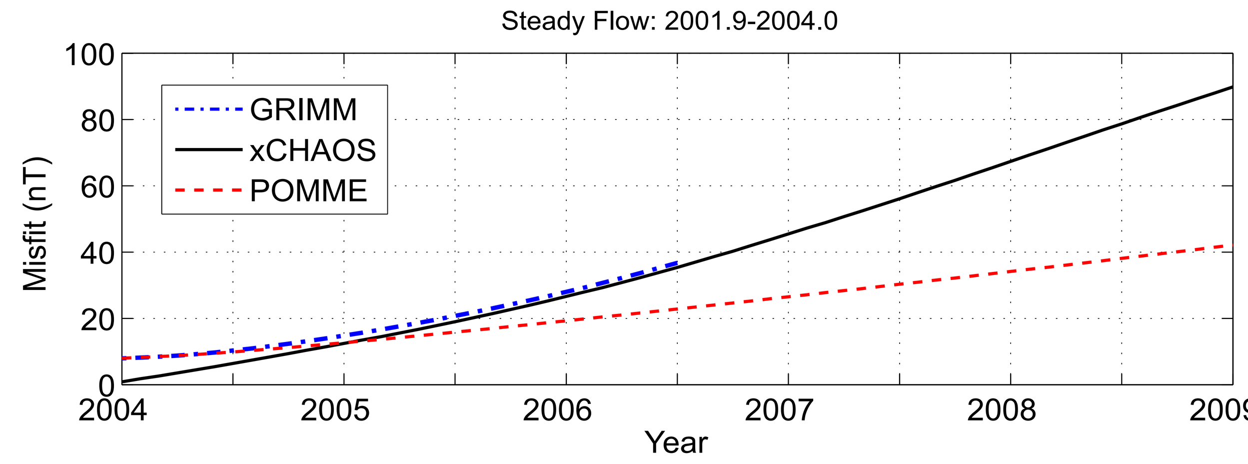


Figure 3: RMS difference (in nT) between the forecast field from a steady flow model generated from data over the period 2001.9–2004.0 and the GRIMM, POMME and xCHAOS satellite field models. Note the GRIMM model spline coefficients extend to 2006.5, while the POMME model is extrapolated beyond 2007.5 using constant SV.

4) Assimilation is not Futile

Is it possible to improve on the results in Figure 3? If the forecast model were combined with information from a low spatial resolution field model, could that improve the RMS misfit between the forecast and the 'true' state of the field?

We investigated the use of an Ensemble Kalman Filter (EnKF) to optimally assimilate data from a relatively 'noisy' field model (as might be developed solely from ground-based observatories) and the forecast field output from a steady flow model. The EnKF is a Monte-Carlo method for optimally combining models of and observational information about a physical process by statistical representation of the associated uncertainties (Evensen, 1994).

Figure 4 shows the resulting RMS misfit using an ensemble of 1000 states and a particular set of noise assumptions for the flow and field models. We concluded that the RMS misfit can be reduced to lower than 25nT with the annual assimilation of low resolution field models. See Beggan and Whaler (2009) for further details.

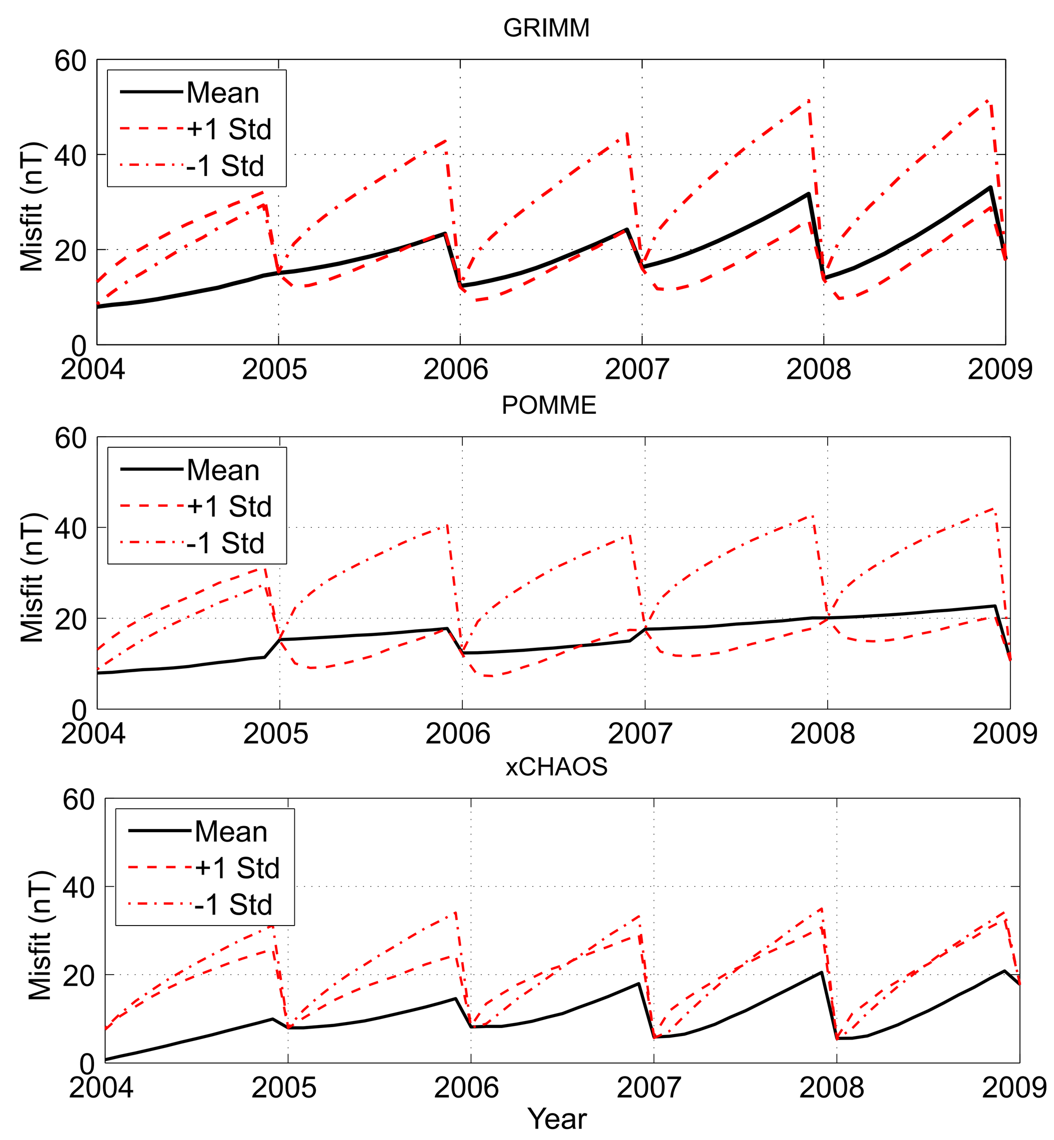


Figure 4: RMS difference (in nT) between a EnKF field forecast with annual assimilation derived from SV generated by a steady flow model from CHAMP satellite data over the period 2001.9–2004.0 and the (top) GRIMM, (middle) POMME and (bottom) xCHAOS field models. Each ensemble was initiated using the xCHAOS field model. Assimilations of noisy measurements from the relevant field model are indicated by jumps in the curves.

The solid black line represents the misfit of the mean Gauss coefficients of the ensemble to the satellite field models, while the dashed lines are misfits of the Gauss coefficients one standard deviation above or below the mean. The middle and bottom panels show that the mean ensembles (solid line) fit to better than 25nT for both the POMME and xCHAOS models over the entire period. Most of the misfit is from the difference between forecast and model at degrees l = 1–4.

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