Geomagnetic Jerks in the Swarm Era

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ABSTRACT

The timely provision of geomagnetic observations as part of the European Space Agency (ESA) Swarm mission means up-to-date analysis and modelling of the Earth's magnetic field can be conducted rapidly in a manner not possible before. Observations from each of the three Swarm constellation satellites are available within 4 days and a database of close-to-definitive ground observatory measurements is updated every 3 months. This makes it possible to study very recent variations of the core magnetic field. Here we investigate rapid, unpredictable internal field variations known as geomagnetic jerks.
Given that jerks represent (currently) unpredictable changes in the core field and have been identified to have happened in 2014 since Swarm was launched, we ask what impact this might have on the future accuracy of the International Geomagnetic Reference Field (IGRF). We assess the performance of each of the IGRF-12 secular variation model candidates in light of recent jerks, given that four of the nine candidates are novel physics-based predictive models.

1. INTRODUCTION

The Earth's internal magnetic field is generated by the motion of the conductive metallic fluid in the outer core. With changes in the motion of the fluid, come variations through time in the shape and intensity of the resulting magnetic field – this rate of change is known as secular variation (SV). While the SV has been observed for several centuries [1] and tracked at fixed points on the Earth's surface in great detail by magnetic observatories for nearly two hundred years, it has been the advent of satellite technology that has provided a significant advance in our spatial knowledge. Detailed information of the changing magnetic field has been provided by satellites in low Earth orbit since 1999. Single satellite missions Ørsted [2], CHAMP [3] and SAC-C [4] have now been succeeded by the three satellite constellation Swarm [5], launched by ESA in November 2013.
Recent studies [6, 7] have shown that the SV is not constant and largely varies on decadal timescales, with periods of near constant change interspersed by rapid variations in the second time derivative of the field, the secular acceleration (SA), known as geomagnetic jerks.
Geomagnetic jerks are most commonly defined as 'V' or 'Λ' shaped features in the SV although other characteristics forms can be identified, as illustrated in Fig. 1. Jerks represent the most rapid observed internally generated magnetic features known and are associated with fast flows at the surface of the outer core [7],

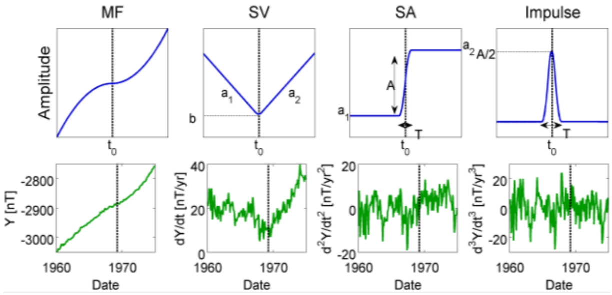

Figure 1. Idealised form of a jerk (at vertical line) (top row) and in monthly mean observations of 1969 jerk in East (Y) component at Eskdalemuir (ESK), UK (bottom row). Columns show successive time derivatives from left to right: the main field (MF), secular variation (SV), secular acceleration (SA) and third time derivative (impulse). Jerk amplitude $A = a_2 - a_1$ is defined in both the SV and SA.

although their generation source is not fully understood. What is clear from the example in Fig. 1, is that higher frequency noise present in observations (predominantly magnetic field signals generated externally to the Earth) can easily distort or mask such features, particularly in the higher time derivatives. For this reason time averages of the field are taken to calculate the SV and often smoothly varying field models are used to analyse spatial features rather than raw observations directly. Several jerks have been documented during the satellite era (see e.g. [6] for a recent discussion and [8] for a review) but only one since the launch of Swarm around 2014[9].
Here we will investigate the 2014 jerk in detail using observatory data compiled for the Swarm mission. We enhance the effectiveness of this analysis by using external field models to provide estimated corrections to the observatory measurements. We also build our own field model using the latest observatory and Swarm data to observe how well the 2014 jerk can be captured soon after its occurrence and assess the impact of the jerk on predictions of SV over the next four years. In particular we are interested in how well each of the nine predictive SV candidate models for IGRF-12 [10], constructed with data up to mid-2014 and providing a prediction of the field from 2015 to 2020, perform when considering the predictions from four of the nine candidate models were based on principles of physics rather than simple mathematical extrapolation.

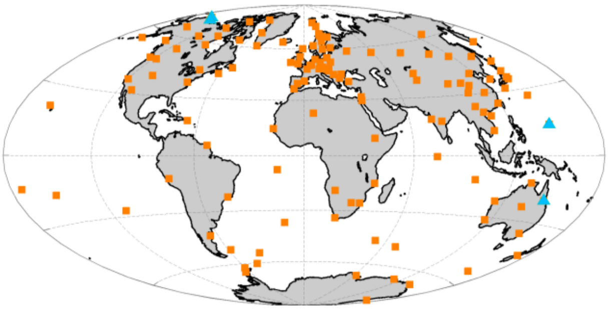

Figure 2. Locations of magnetic observatories providing hourly mean data for AUX_OBS_2. Highlighted observatories (blue triangles) relate to Fig. 4, with BRW and JCO, Alaska markers overlapped.

2. DATA AND MODELLING

2.1. Observatory Data

As part of the support for the Swarm mission which delivers 1 Hz vector and scalar data from each satellite within 4 days of measurement, close-to-definitive hourly mean vector magnetic values from over 150 ground observatories (Fig. 2) are collated by the British Geological Survey (BGS) from INTERMAGNET and in the capacity of the World Data Centre (WDC) for Geomagnetism, Edinburgh. These observatory data form the Swarm *Level* 2 product *AUX_OBS_2* [11] and currently updated on a quarterly basis. Plans are being developed to increase this frequency significantly, moving towards more prompt delivery of minute and second resolution data. This combination of extensive, accurate spatial and temporal data allows rapid modelling and analysis of recent SV.

To study the 2014 jerk we use observatory data directly. Since magnetic observations capture many sources of magnetic fields – from e.g. the core, lithosphere, ionosphere and magnetosphere – we utilise geomagnetic field models to estimate the contributions of each source at a given time and location, as illustrated in Fig. 3. We remove an estimation of the large scale, time varying external and induced fields from the observations using the CM4 [12] (ionosphere) and CHAOS-6 [7] (magnetosphere) models, keeping only the known internal field. We then calculate Huber-weighted monthly mean values from the observations using all hourly mean values in order to reduce the impact of remaining high frequency external signals and noise. The SV is then computed as annual differences such that, for example the North (X) component at month *t*, $\dot{B}_X(t) = B_X(t+6) - B_X(t-6)$. This also further smooths the observations in time and removes the time invariant lithospheric field contribution.

2.2. BGS Model

In order to study the global signature of SV during the Swarm era and to compare up-to-date analyses with the predictions of IGRF-12, we use a model (hereafter referred to as the BGS model) derived from the BGS

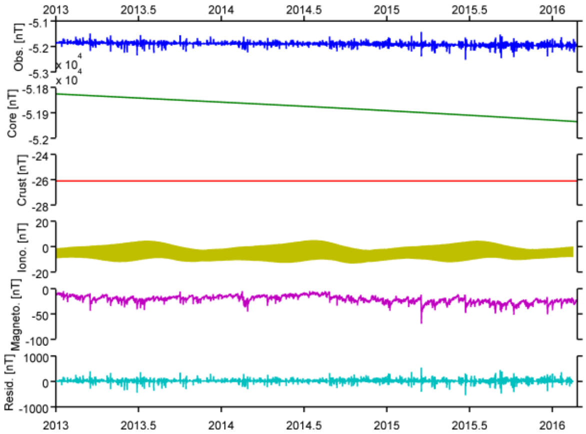

Figure 3. Example of separated field sources for observatory at Abisko (ABK), Sweden using the BGS core and lithospheric model, CM4 ionospheric model and CHAOS-6 magnetospheric model. Top-to-bottom are shown observed hourly mean vertical (Z) component, then contributions from the core, lithosphere (crust), ionosphere, magnetosphere and unmodelled data residuals.

geomagnetic modelling system. A detailed description of the modelling approach can be found in [13] which describes the BGS candidate model for IGRF-12. Our approach here follows the same principles as [13] but focusses on the core field component and uses the latest Swarm and AUX_OBS_2 data as of March 2016 for the duration of the Swarm mission (November 2013 to March 2016). In brief, the model describes the internal geomagnetic field as the gradient of a potential $\boldsymbol{B}(t) = -\nabla V(t)$, expanded in spherical harmonics (SH) of degree *n*, order *m* as

$$V = a \sum_{n=1}^{15} \sum_{m=0}^{n} (g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi) \left(\frac{a}{r}\right)^{n+1} P_n^m(\cos\theta), \qquad (1)$$

where a is the Earth's mean radius and P_n^m are Schmidt semi-normalised associated Legendre functions, in spherical coordinates of radius *r*, geocentric co-latitude θ and geocentric longitude ϕ. The time dependence of Gauss coefficients, g_n^m and h_n^m, describing the core field to degree 15 is governed by order 6 B-splines [14] using annual knot spacing and regularised to minimise the second and third time derivatives of the squared radial magnetic field at the core-mantle boundary and Earth's surface, respectively.

2.3. IGRF

The IGRF is a SH model of the core field, updated on a quinquennial basis [10], most recently with IGRF-12. It is formed as an amalgamation of several candidate models produced by various institutions and research groups. It provides snapshot models through time, most recently to SH degree 13 at 2015.0, and a predictive linear SV model to SH degree 8 valid for the subsequent

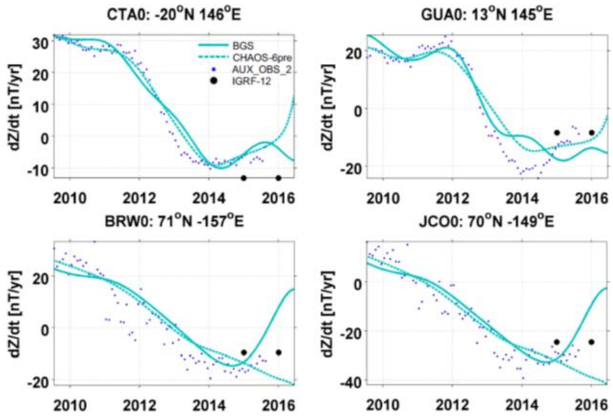

Figure 4. Vertical (Z) component of SV at Charters Towers (CTA), Australia and Guam (GUA) showing late-2013 / early-2014 jerks and at Barrow (BRW) and Jim Carrigan Observatory (JCO), Alaska showing late-2014 / early-2015 jerks. Observatory locations are highlighted (blue trinagles) in Fig. 2. BGS model (solid line) and CHAOS-6 (dashed line) core field are shown with monthly mean data (small points) and predictions of IGRF-12 (large points). The '0' appended to each observatory abbreviation code signifies a single unbroken series was available.

5 years to 2020. Generally the SV candidates are constructed by linear extrapolation of Gauss coefficients from the final periods of the parent models, in this case built with various combinations of Swarm and observatory data up to mid-2014. Of interest to us is the fact that four of the nine IGRF-12 SV candidates, from BGS, ISTerre, NASA GSFC and IPGP, constructed their SV candidate models from physics-based methods rather than mathematical extrapolation. These methods were: forward advection of core surface flow velocity and acceleration; forward integration of a stochastic flow model; forward propagation of an assimilated geodynamo model; forward advection of core surface flow under frozen-flux, steady velocity, respectively.

3. JERKS DURING THE SWARM MISSION

Reference [9] was the first to point out the presence of a jerk around 2014 in quasi-definitive observatory data which detailed SV to March 2015 and in the updated CHAOS-5x_v3 model [15]. Regions of strong SA were noted, particularly in the South Atlantic / Africa, extending up into Europe and the north-western Atlantic as well as in Australasia. With AUX_OBS_2 data providing SV to September 2015 and the BGS model extending to March 2016 we therefore reassess the extent and characteristics of the 2014 jerk and more recent developments.

We use the jerk detection algorithm (and parameterisation) of [8] with a window length of 4 years to identify jerks in the monthly mean data. We include buffers of observatory data from 2009 to the start of the Swarm mission in November 2013 and of null values from September 2015 to March 2016 to allow analysis of

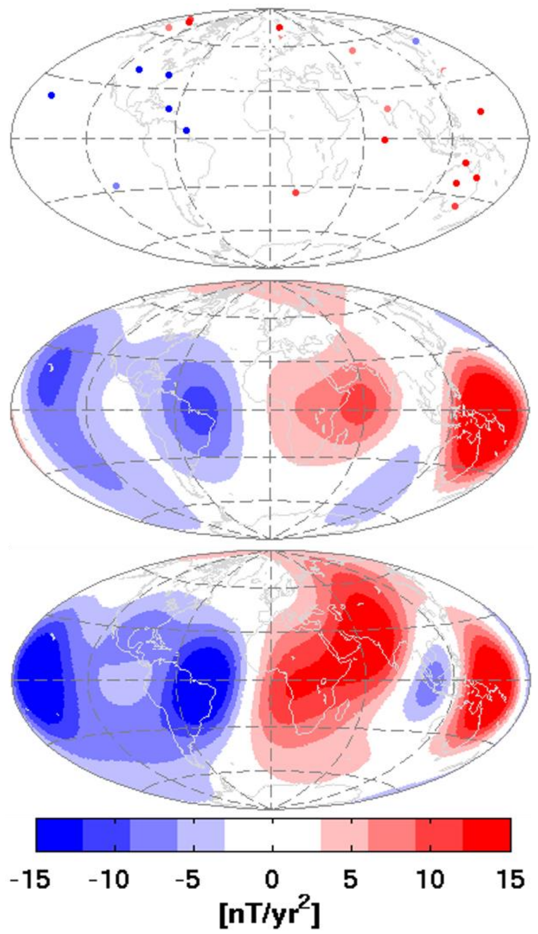

Figure 5. Amplitude of jerks detected in vertical (Z) component monthly mean data between 2013.00 and 2016.25 (top), SH model of the jerk amplitudes (middle) and ΔSA from CHAOS-6 model at 2014.00 (bottom). Both models are expanded to SH degree 13 at Earth's surface.

jerks close to the ends of the period of interest.

We confirm the presence of widespread jerks across much of the globe, succeeding and distinct from the jerks seen around 2011 as described by [6]. Jerks are detected throughout 2013 and 2014, extending into early 2015 at some observatories. We detect the latest examples of jerks in some regions not identified by [9], such as Alaska. This is shown in Fig. 4, where we compare monthly mean observations to the BGS and CHAOS-6 models, as well as the predictions of IGRF-12. Several points can be made regarding Fig. 4. The smoothing effects of temporally regularised, limited resolution models are clear compared to the sometimes sharp variations of data, e.g. at Guam, and jerks can be underestimated as well as smoothed in time. In addition, the impact of just 4 months additional data and model parameterisation in the BGS model compared with CHAOS-6 is significant – note that B-splines are not effective tools for prediction, despite regularisation, and end effects can differ greatly with different constraining data. Hence in some regions the IGRF-12 SV prediction fits well after 1 year, where a jerk occurred before the model was constructed (e.g. Guam or even where it had not yet clearly occurred e.g. Alaska), but in other regions predicted SV has already diverged from more recent observations (e.g. Charters Towers).

The distribution of detected jerks and their estimated amplitudes can be mapped by performing a SH fit, although due to the sparse distribution of observatories some smoothing is necessary [16]. The detected jerks and resulting SH model are shown in Fig. 5 along with the ΔSA of CHAOS-6 taken across a year centred on 2014.0. It can be seen that as with other known jerks, amplitudes are contiguous and regionally grouped [8, 17]. A strong agreement is found between the SH fit to detected jerk amplitudes and CHAOS-6 ΔSA, with a correlation coefficient of >0.8. A weaker correlation of 0.5 is seen between the SH jerk model and the ΔSA of the BGS model, indicating that the SA is not as well captured in this case, perhaps because of the short 3.25 year span of the model or our regularisation choice.

Interestingly, while all models pick up the high SA of the detected jerks over the Pacific, South America and Australasia, they also show high SA over eastern Africa / central Asia that is not obvious from the jerks detected in observatory data. Our SH fit to jerk amplitudes gives a less extensive SA patch in this region, while CHAOS-6 shows higher SA extending across much of Africa and into Central Asia. It is likely that the paucity of observatory data and the additional Swarm data and second and third time derivative regularisation of the CHAOS-6 model compared to our simple fit to detected jerks in observatory data leads to this discrepancy. These regions of high SA appear to agree with the observations of [6] showing pulses of high SA between jerk occurrences.

We note that neither the BGS model nor CHAOS-6 shows the SA to be as high as detected amplitudes suggest at high northern latitude observatories (e.g. Alaska; Hornsund, Svalbard (HRN); Paratunka, Russia (PET)) where we detect the most recent jerks. It is likely that such smooth, large-scale models cannot capture the true spatial complexity of the jerk signals, particularly at high latitudes where external field noise is most prevalent.

4. PREDICTION OF SV

The non-linear SV we observe at jerks is an enormous challenge for predictive modelling of SV. Forecasts of the SV, particularly when it is large and rapid, is important to numerous commercial and academic activities from navigation (including directional drilling in hydrocarbon exploration) to satellite hazard estimation. Considering the examples in Fig. 4, if a linear extrapolation were to be made using the final 6–12 months of data so close to a jerk, the relative timing of the jerk at each given location would greatly influence the predicted result. Of course extrapolated SV predictions are generally made from the Gauss coefficients themselves rather than data series, but this provides a simpler and more tangible example of a similar process.

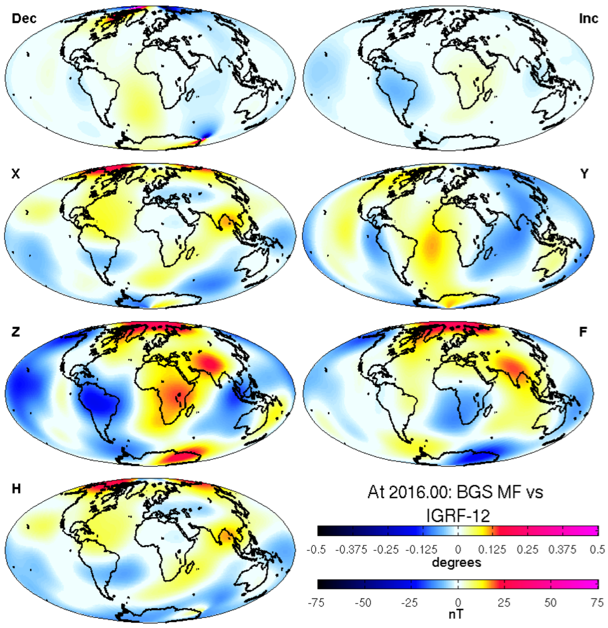

Figure 6. Difference maps between core field of the BGS main field (MF) model, using data to March 2016 and the IGRF-12 prediction, at 2016.0. Both models were expanded to the IGRF resolution of SH degree 13. Maps of declination (Dec) and inclination (Inc), in degrees, North (X), East (Y) and vertical (Z) components, total (F) and horizontal (H) intensity, in nano-Tesla, are shown.

We can assess the performance of the IGRF-12 SV prediction in light of the recent jerks by comparing with the BGS model at 2016.0, as shown in Fig. 6. Obvious differences arise between the two models, with the vertical (Z) component differences peaking at >|25| nT. Indeed, the greatest vertical component differences match well with the regions highlighted maps shown in Fig. 5. The overall root-mean-square (RMS) difference between the BGS model and IGRF-12 prediction at 2016.0 is 15.7 nT with a similar value found for differences between IGRF-12 and CHAOS-6, which itself agrees to within 6.6 nT RMS with the BGS model. This is a sizeable difference given the previous (now definitive) IGRF snapshot model at 2010.0 which agrees with CHAOS-6 and a similar BGS model to within 2 nT RMS. The somewhat unfortunate timing of a widespread jerk so close to the release of IGRF-12 means that the SV prediction is likely to diverge further from the real SV – unless a future subsequent jerk brings it back in line. This is not an unrealistic possibility given that, as for example [6] show, jerks have been observed more frequently during the satellite era than in the previous century, occurring every 3–4 years.

To assess the performance of the individual IGRF-12 SV candidate models we compare the power spectra of

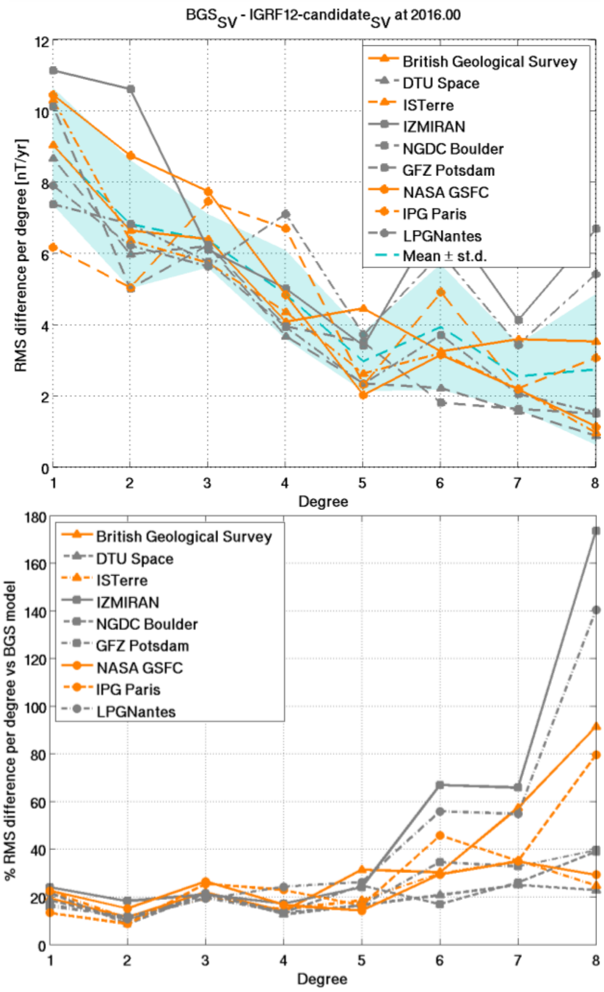

Figure 7. RMS differences per SH degree between the nine IGRF-12 SV candidate models and the BGS model (top) and as percentages of the BGS model power (bottom), at 2016.0. Candidates with physics-based SV predictions are shown in orange, mathematically extrapolated SV models in grey. Note that the BGS model mentioned in the legend is the BGS candidate model for IGRF-12, not the model described here.

differences at 2016.0, at the Earth's surface, between each candidate model and the BGS model. The RMS differences per SH degree and percentage differences from the BGS model per degree are shown in Fig. 7. Of the nine candidate models, none performs significantly better or worse than the others. It is also clear that none of the models is consistently further than one standard deviation from the mean RMS difference from the BGS model, indicated by the shaded area in the upper plot of Fig. 7. The absolute RMS differences suggest that the lowest SH degrees (largest spatial scales) are captured most poorly, the trend decreasing and flattening at a stable ~3.5 nT/yr above SH degree 4. The percentage RMS differences (lower plot of Fig. 7) however, suggest that misfit to the BGS model is consistent at around 20% error for all candidates at SH degrees 1 to 5 before increasing thereafter. In both cases there is no obvious distinction between the accuracy of the physics-based SV models and the mathematically extrapolated ones.

While this is a discouraging finding on the face of it for physics-based SV models, it is likely a consequence of the 2014 jerk, just after the construction of IGRF-12, and the generally linear SV otherwise, rather than a fundamental flaw in the approach. Nonetheless it is a reminder that without full knowledge of the dynamic causes of jerks – significant and frequent features of the SV – our ability to predict the field will be limited. None of the physics-based SV models appears to capture the variations of the jerk at the appropriate temporal or spatial scales. We can only speculate what the case would be but if a jerk were to occur immediately before an IGRF production date, this might demonstrate more readily the abilities of such physics-based SV forecasting models.

5. CONCLUSIONS

Here we have shown that the prompt delivery of high quality Swarm and observatory data enables the analysis of the geomagnetic field in an up-to-date fashion not previously possible. We have demonstrated this, both by analysing the observatory data directly and by constructing a field model from the observations, in order to investigate the rapid phenomena of geomagnetic jerks. Indeed it is currently only possible to discuss a jerk occurrence after the fact. The rapid availability of excellent observations has allowed us to investigate the impact of the unpredictable SV of jerks on the recent predictions of IGRF-12.

We find geographically widespread evidence of jerks during the Swarm era, from 2013 to 2016, in agreement with, and extending in time, the observations of [9] and extending the pulsating SA of [6].

We show that up-to-date data can have a significant impact on a core field model with an RMS difference at 2016.0 of 15.7 nT between the BGS model, built with data to March 2016, and IGRF-12, built with data to mid-2014.

By comparing the physics-based and mathematically extrapolated SV predictions of the nine IGRF-12 candidate models to our BGS model we show that there is no obvious distinction between the performance of models in the two categories – all fail due to the unpredictable, non-linear behaviour of jerks. This emphasizes the importance of understanding the rapid dynamics behind geomagnetic jerks.

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