Dear Rick Saltus,

we thank for the very constructive feedback and to rise questions about the important aspect of the data uncertainties in the magnetic anomaly compilation. Implementing your comments and corrections clearly improves the quality of our manuscript.

We address your various comments and questions individually, beginning with your review letter and subsequently the annotations made directly in the manuscript.

Best Regards

Björn Heincke

Responses to the main reviewer letter:

This is an excellent presentation of a state of the art compilation of magnetic survey data to produce a comprehensive data grid. The authors provide clear discussion of the approach and rationale for their modeling decisions.

I have made a few comments and suggestions as shown in the attached annotated manuscript.

One recurring comment deals with the use of the term "error" when "uncertainty" is meant. Errors can be positive or negative whereas uncertainty indicates the probable range in which the true value is likely to occur. You can only know error if you know the truth for comparison.

ANSWER: We fully agree that we used an oversimplified terminology by not distinguishing "error" from "uncertainty". This is now corrected in the manuscript.

The authors deal with uncertainty in a general probabilistic way - they mention the initial data uncertainty attributed to the original survey data (ranging from 5 to 50 nT as an average attribute per survey). This value is used for weighting of the data in the inversion for equivalent source values. They mention the overall goodness of fit for the equivalent source combined model relative to the original data. They also explain the method for solving in the inversion for the probable DC offset between the individual surveys. An addition source of uncertainty is the long wavelength uncertainty in the LCS-1 model incorporated in the final grid. I realize it is difficult to propagate uncertainty through all these steps, but I think it is worth some discussion and, ideally, the authors would produce some sort of overall uncertainty grid to accompany the data grid.

ANSWER: We fully understand this concern and we have added some more discussions about the data uncertainty for individual steps:

- We now include an additional figure in the Appendix illustrating the distribution of uncertainties when no shift correction is applied in the equivalent source modelling. It reveals pronounced systematic errors along individual survey lines, which lead to visible artifacts in the resulting magnetic anomaly map. In contrast, the same test performed with a constant shift correction enabled (see Figure 5) demonstrates that most of these systematic errors are effectively mitigated, and no apparent artifacts remain. This highlights the critical importance of applying shift corrections in the inversion.

- We describe now that also the satellite model contains errors and that these can be significant for high latitude regions. Since we incorporate the long wavelength components of the satellite model after the equivalent source modelling (inversion) is performed, uncertainties in the satellite model can be currently not evaluated or mitigated in our current approach. We therefore propose in the discussion that it is useful to modify the setup in a way that satellite data are added also at the inversion stage in future.

Another approach to validating the grid and uncertainty would be to identify trusted long survey lines that were not included in the model for comparison with values extracted from the grid.

ANSWER: There is a long survey line that is not used in the compilation extending offshore Greenland from the northwest, across the southern region, to the central eastern coast. Unfortunately, this line dates back to the early 1980s and was acquired without GPS positioning. Furthermore, it appears that no proper base station correction was applied to its data. A comparison of this line with all three compilations (GREENMAG, CAMP-M and GAMMA-5) reveals anomalies that are absent in any of the three compilations. We conclude therefore that the line cannot be trusted.

However, even without additional discussion/assessment of grid uncertainty, this paper is excellent and worthy of publication. Similar scale data compilations to date have generally not included detailed uncertainty assessment. Similarly, many authors conflate the terms error and uncertainty and most readers can discern the difference.

Responses to comments made in the manuscript:

Line 104: The equivalent source method allows for propagation of uncertainty from data to models - did you consider using weighted least squares to propagate uncertainty on a cell by cell basis?

ANSWER: Yes. We apply weighted least squares to the data term of the inversion's objective function to estimate the susceptibilities (of unit volumes) for the equivalent sources. During

inversion stochastic data errors are reduced, but systematic errors are assigned to the equivalent sources. Systematic errors can then be diminished by some adaption of the inversion setup (e.g., by implementing some shift corrections as done in our approach).

Line 138: I don't think this is correct - I think that both the vector mag data and gradients were used.

ANSWER: We checked the publication of Olsen et al (2017) once again. They indeed only use gradient data from Swarm and CHAMP satellites to build the LCS-1 model.

Line 152: Is there a reason that the computationally much simpler monopole source was not selected?

ANSWER: We chose dipoles as equivalent sources since they provide a more realistic physical representation of the true magnetic behaviour than monopoles (this benefit is mentioned now in Section 3.1).

Moreover, the use of magnetic dipoles enables consideration of temporal variations in both the amplitude and direction of Earth's main magnetic field. This, in turn, allows to reduce during the inversion process inconsistencies between datasets that are associated with their different acquisition times. Such adjustments are not feasible when magnetic monopoles would be used.

Since we did not describe this benefit, we have now added a short subsection (Section 3.3.4) that describes how Earth's main magnetic fields at different times are implemented in the inversion for both the equivalent sources and measurement locations.

Line 247: It would be awesome to produce and distribute grids with specifications consistent with the global grids such as EMAG and WDMAM - this would aid in the incorporation of this new compilation into the next updates of these grids.

ANSWER: We fully agree that this is a great benefit. We added a sentence that it is possible to use parameters that are consistent with the ones of the global magnetic compilations such that it can be optimally integrated into them.

Line 254: It would be good to note here that while the satellite derived spherical harmonic models are good on average for the globe, there is poorly defined local uncertainty for these models, especially at higher latitudes. It would be good to produce a version of GREENMAG that only includes the wavelengths shorter than the satellite reference model.

ANSWER: We discuss now uncertainties of the satellite model in section "5.3 Replacement with satellite data" (see answer to comment "*Line 392: While ...*").

It would be straightforward to construct a version of the GREENMAG model that includes only shorter wavelengths than the satellite model by simply removing degrees n < 133 from the aeromagnetic model. However, we do not see any clear applications that would require such a short-wavelength model, and therefore we have chosen not to present it here.

Line 305: errors can be positive or negative - you are referring to uncertainty

ANSWER: We agree that we had not used the correct terminology here.

Line 307: again, you mean uncertainty, not error

ANSWER: Done

Caption of Figure 3: Line uncertainty

ANSWER: Done

Line 324: missing word "height"

ANSWER: Done

Figure 4: I suggest making the color scale labels even numbers between + and - 250 nT. This is a nearly linear ramp with 51 and 52 nT intervals - labeling on even numbers would be much easier to understand.

ANSWER: We agree with the reviewer. We have changed the color scale labels for all figures (5, 6, 7, 8, 9, C1, D1 and E1), where this color scale was used.

Line 373: Uncertainty

ANSWER: Done

Caption of Figure 5: uncertainty - error is plus or minus and you only know it if you have the truth for comparison

ANSWER: In this case, it should be errors since the histogram presents positive and negative values.

Line 388: This is not the correct word - use "shows the most southern block" instead

ANSWER: Done

Line 392: While the LCS-1 model achieves a good global fit to the satellite data, local features have uncertainty that is not well characterized, particularly at high latitude. I think it is worth pointing out that there is some uncertainty in the model, especially for relatively localized features...

ANSWER: We agree that it is inappropriate to omit the uncertainties associated with the satellite model. This aspect is particularly critical, as our approach does not fit the long-wavelength components of the satellite data during inversion, but instead, these are directly substituted within the spherical harmonic (SH) expansion. This means that the data uncertainties of the satellite data were not evaluated (or reduced) in our approach.

We have therefore added now a section pointing out that satellite-based models have uncertainties for small-scale lithospheric magnetic features and that these are especially high in the polar regions.

Figure 8: I suggest mentioning the direction of shading used as this affects the trends that are enhanced

ANSWER: We mention now the illumination direction in the caption.

Figure 8: I suggest fixing this color scale to have regular 50 nT intervals between + - 250

ANSWER: We agree with the reviewer (see above). We have changed the color scale labels for all figures (5, 6, 7, 8, 9, C1, D1 and E1), where this color scale was used.

Figure 9: ditto comments on color scale and mention of shading direction

ANSWER: We mention now the illumination direction in the caption.

Appendix D: This heading is in the wrong place

ANSWER: The LaTeX compiler did here strange things. We have moved the heading to the right place.

Other changes made in the manuscript:

Only parts of the shift correction implementation were originally presented in the Appendix B. Specifically, we described its integration within the data term of the objective function, but omitted its role in the regularization term to keep the methodological section concise.

However, given the importance of shift correction for eliminating systematic inconsistencies between datasets, we now consider it more appropriate to present the full implementation. Accordingly, we have added the corresponding modifications to the regularization term.

Dear Thorkild Rasmussen,

we are very grateful for your feedback and comments that much improve the quality of the manuscript. In particular, we consider your comment to discuss the equivalent source models in some more detail as very useful and have added now explanations a) why we chose dipoles as the equivalent sources and b) why we have not explicitly considered the remanent magnetization component in our model.

We address your various comments and questions individually, beginning with your review letter and subsequently the annotations made directly in the manuscript.

Best Regards

Björn Heincke

Responses to the main reviewer letter:

The manuscript by Heincke et al. on compilation of magnetic data for Greenland is a very important contribution and based on sound modelling and processing principles. I have attached an annotated version with suggestions for modifications (grammar mainly) and some questions/comments the authors should consider.

I would like to see some discussion on the actual "models " that are the output from the inversion, even though that they are not "true physical" geo-models. In particular, I note (see comments in annotated manuscript) that only induced polarization is assumed. What kind of equivalent source model is produced offshore where you have reversed polarity of the magnetic anomalies. What kind of pattern on equivalent source strength (positive/negative) is revealed? How does remanent magnetisation influence the inversion?

ANSWER:

- We chose dipoles as equivalent sources since they provide a more realistic physical representation of the true magnetic behaviour than monopoles (this benefit is mentioned now in Section 3.1) and their responses are much faster to compute than the ones of finite bodies as e.g. pillars.

   Moreover, the use of magnetic dipoles enables consideration of temporal variations in both the amplitude and direction of Earth's main magnetic field. This, in turn, allows to reduce during the inversion process inconsistencies between datasets that are associated with their different acquisition times. Such adjustments are not feasible when magnetic monopoles would be used.

   Since we did not describe this benefit before, we have now added a short subsection (Section 3.3.4) that describes how Earth's main magnetic fields at different times are

implemented in the inversion for both the equivalent sources and measurement locations.

- It is an interesting question, if it is needed to explicitly consider the contribution of the remanent magnetization in the equivalent source model (and inversion). We had a similar discussion among the authors at the beginning of the project and we concluded that the remanent part can be considered as negligible in very most cases.

  This can be explained as follows: A dipole component oriented orthogonally to the main geomagnetic field produces magnetic field vectors at nearby observation points whose directions deviate significantly from the one of the main geomagnetic field. Since the total magnetic anomaly is determined by projecting the dipole field onto the direction of the main geomagnetic field (see Eq. 3), the contribution of an orthogonally oriented dipole component is comparatively small.

  In practise, it can be checked whether dipoles used as equivalent sources adequately describe the magnetic field in areas dominated by remanent magnetization by considering the data misfits at nearby observation points. In our inversion test, we did not observe any elevated data misfits in areas that are dominated by magnetic remanence such as the ocean floor with its magnetic stripping patterns. This indicates that our model is able to properly fit the data, even though it does not explicitly consider the remanence.

  We have added now a discussion of this observation in Section 5.1.

Responses to comments made in the manuscript:

Line 12: change to "merging"

ANSWER: Done

Lines 21-22: The sentence needs rephrasing

ANSWER: We have changed the sentence to "Since areas insufficiently covered by airborne magnetic surveys can, moreover, be supplemented with lower-resolution satellite data, ... "

Line 26: change to "trace"

ANSWER: Done

Line 33: change to "exploration"

ANSWER: Done

Lines 40 – 45: I suggest to include a reference also to GEOPHYSICS, VOL. 67, NO. 2 (MARCH-APRIL 2002); P. 546–554, 6 FIGS., 3 TABLES.10.1190/1.1468615. Compatibility of high-altitude aeromagnetic and satellite-altitude magnetic anomalies over Canada. by D. Ravat, K. A. Whaler, M. Pilkington, T. Sabaka, and M. Purucker

ANSWER: We have added this reference in the introduction.

Line 49: change to "wavelength"

ANSWER: We have changed "frequency" to "wavenumber".

Line 89: change to "weight"

ANSWER: Both "regularization strengths" and "regularization weights" are commonly used terms in literature about inversion problems. We keep "regularization strengths" here.

Line 128: change to "acquired irregular"

ANSWER: We have replaced "unsystematically" with "irregularly".

Line 151: change to "magnetic"

ANSWER: We have changed "such as point masses and dipoles" to "such as magnetic monopoles and dipoles".

Lines 156-158: The ocean bottom has ages much less than the latest polarity reversal, so a reasonable assumption is that main contributions (or dominant) to the observed field offshore is remanent magnetization. Remember here that the magnetic response is zero for a horizontal slab (assuming flat Earth) with homogeneous magnetisation. Thus, provided that the continental drift is relatively small N-S, and mainly west-east wards, the induced field is in general small compared to the remanent field contribution.

ANSWER: We have addressed this aspect already in our reply to the main comment (see above).

Line 156: add "apparent"

ANSWER: Done

Line 157: change to "aligned along the direction of the main geomagnetic field"

ANSWER: Equation 2 assumes that all magnetization is induced and no remanence exists - even not along the direction of the core field. Therefore, we have changed the sentence slightly differently as proposed by the reviewer: "[...] This implies that all magnetization is assumed to be induced and thus aligned with the direction of the main geomagnetic field (no remanence and no field components orthogonal to the core field) [...]"

Line 157: add "orthogonal to core field"

ANSWER: See response to the previous comment

Line 187: delete "the"

ANSWER: Done

Line 242: Clearly, the Laplace equation is valid but is this a necessity for using equations 1-4? This is first of, all important /inherent for the use of spherical harmonics representation

ANSWER: The reviewer's comment is correct that the Laplace equation is not strictly required to apply equations 1 - 4, but the Laplace equation states that the field from equivalent sources fully represents the magnetic field generated by all sources located beneath the ES layers. To make this clear, we have added to the sentence: "[...] the complete magnetic field originating from the subsurface (underneath the ES layers) is represented by the fields from the equivalent sources and [...]".

Line 267: "first" is a somewhat arbitrary term although you do start up with estimation of C1. Use "lower most" instead.

ANSWER: Done

Line 272: delete "Typically"

ANSWER: Done

Line 298: change to "sufficiently"

ANSWER: Done

Line 300: change to "weights"

ANSWER: Both "regularization strengths" and "regularization weights" are commonly used terms in literature about inversion problems. We keep "regularization strengths" here.

Line 302: change to "sparsely"

ANSWER: Done

Line 324: the term "height" in the modelling is with reference to spherical earth so this introduce some thought for how to interpret data in relation to sea-level? I guess it becomes a little too philosophical to enter a discussion on this, but maybe something to consider for the future. Since the final data are only the anomalous field, I guess not of any concern here.

ANSWER: We agree with the reviewer and appreciate this comment – and in the most recent version of our program the flattening of the earth at the poles is considered. It would be even more appropriate to estimate the exact radius of the WGS84 ellipsoid at every equivalent source and measuring location. But then we need to find solutions that will not slow down calculations too much.

Line 324: change to "height"

ANSWER: Done

Line 327: change to "plane"

ANSWER: Done

Line 336: Any consideration on aliasing? any low-pass filter used prior to resampling?

ANSWER: The measured data typically have finer intervals than those obtained after resampling such that aliasing effects do not arise.

Lines 362 and 366: delete "(" and ")"

ANSWER: Done

Line 382: change to "heavily dependent on"

ANSWER: Done

Line 397: change to "low data density"

ANSWER: We have rephrased the sentence to become clearer.

Lines 402-403: I guess this would be interpolation across lines, not extrapolation?

ANSWER: Done. We agree with the reviewer that "interpolation" is the better suited term here.

Line 405: change to "in many places"

ANSWER: Done

Line 416: Remove line-break

ANSWER: Done

Line 421: magmatic or magnetic?

ANSWER: We have changed it to "magnetic".

Line 488: delete "now"

ANSWER: Done