Response to interactive comment RC1 on egusphere-2022-59 – "In-Situ Calibration of the Swarm-Echo Magnetometers" by Robert M. Broadfoot et al. by Mark Moldwin on 19 Apr 2022

We would like to thank the referee for the constructive comments and suggested changes. Mark Moldwin suggested several excellent changes to the manuscript and raised important questions that we address below. Referee comments are in plain text, our response is in italics, and any changes made to the manuscript are in "quoted italics".

This paper describes an in-flight calibration method for the CASSIOPE/e-POP, now known as Swarm-Echo, satellite that was launched in 2013 and included two fluxgate magnetometers on a shared boom. Several issues with the attitude determination system, failure of reaction wheels over time, and the natural drift of off-set and gains of the fluxgates contributed to the magnetometer data becoming less reliable. The paper describes applying a method to use the Earth's model geomagnetic field during quiet times and some rules on when to trust or discard attitude determination estimates to create a new "clean" magnetometer data set.

This is a useful paper describing the new calibration methodology and will enable expanded scientific use of the SWARM-ECHO magnetic data set.

Specific and General Questions interspersed below.

1. Line 11: "calibration performed between on data from January 3, 2014, to January 30, 2021"

   This was a typo missed in our initial review, the text now reads:

   "Here we present the results of an in-situ calibration performed on data from January 3, 2014, to January 30, 2021."

2. What is the length of the boom and the distance to the two magnetometers?

   Boom length is 92.9 cm from center of hinge to end. There is 32 cm of separation between the two magnetometers center-to-center.

   Text was added on line 24 to address the length of the boom and magnetometer separation:

   "…separated by 32 cm center-to-center on a 92.9 cm carbon fiber boom (Figure 1)."

3. Line 20, for comparison – what is the orbital altitude of e-POP compared to the other SWARM spacecraft? Are there any "conjunctions" that can be used to calibrate magnitude (and with field-line tracing) the direction of the field between the SWARM spacecraft?

The original Swarm spacecraft have roughly circular orbits at ~450 km for A and C and >500 km for B. e-POP was considered to be a desirable addition to the Swarm constellation because the orbit is highly *elliptical with perigee at ~330 km and apogee at ~1500 km at launch. As such, it sweeps out a broader range of altitudes that Swarm A/B/C. However, there are >3000 conjunctions between Swarm-E and Swarm-A/B/C where the spacing between Swarm-E and another Swarm satellite is less than 400 km, which we expect we will be able to make use of for further calibration and scientific purposes in the future.*

Currently, the MGF residuals have an average rms error of ~10 nT compared to the Chaos model compared to the Swarm VFM average residuals of ~3 nT making MGF the dominant noise source. Until the MGF residuals are calibrated down below the Swarm VFM/Chaos residual level the before field-line tracing offers a benefit that overcomes the spatial coverage advantage of calibrated against a model field.

Text has been appended to the end of the paragraph starting at Line 20 to inform the reader of the difference in orbits, it reads:"The original Swarm spacecraft have roughly circular orbits at ~450 km for A and C and >500 km for B. e-POP was considered to be a desirable addition to the Swarm constellation because the orbit is highly elliptical with perigee at ~330 km and apogee at ~1500 km at launch. As such, it sweeps out a broader range of altitudes that Swarm A/B/C."

4. Line 34: Suggest breaking last clause into separate sentence…" attitude. However that time interval is beyond the scope of this manuscript."

   We have implemented this correction, and the line now reads:

   "…the spacecraft into a permanent spin-stabilized sun-pointing attitude. However, that time interval is beyond the scope of this manuscript."

5. Line 65, 125: "data have…"

   Line 65 now reads:

   *"We assume that the raw sensor data have error in offset (**b**)…*".

   Line 125 now reads:

   "Early mission attitude data were generated only as Yaw-Pitch-Roll (YPR) values using…".

6. Line 135: What is SQUAD/SLERP?

   Slerp stands for spherical linear interpolation and refers to interpolating between two orientations by moving at constant speed along a circular arc (as opposed to linear interpolation or lerp which idealizes the change in orientation by using linear polynomials and tends to result in very large *angles of arc between each interpolation point). This is sufficient if there is a small enough change between orientations and can treat each interpolation between two points as isolated, or either you don't know or don't really care if other changes in orientation exist before or after.*

SQUAD or Spherical QUADrangle interpolation is a series of slerp interpolations that assumes that other orientations exist before, during, and after the current interpolation between the two points. It smooths the connections between the interpolations as it does not treat each interpolation as an isolated event. This has roots in computer animation and is useful for smoothing movement between multiple animation frames. This of course translates well to spacecraft attitude as the craft is constantly changing orientation while moving along the orbital path.

The line has been edited to improve clarity and correct one of the acronyms, and now reads:

"Switching to a Spherical linear interpolation (Slerp) or a Spherical QUADrangle (SQUAD) (Shoemake, 1987) interpolation rather than per-element interpolation further improved the robustness of the attitude transform by enforcing continuity and smoothness of the attitude solution over multiple measurement points which is appropriate for a physical spacecraft moving in physical space ."

7. Line 151; Is "&" used intentionally instead of "and"?

   That is simply a mistake made when transcribing the notes from one of the co-authors. The line now reads:

   "Following this, attitude solutions derived from the coarse sun sensors and bus magnetometer are considered."

8. Line 164: "metadata are…"; Line 165: "and are included"

   Line 164 now reads:

   "Supplementary metadata are also derived from these definitive solutions…".

   Line 165 now reads:

   "…the raw data source to be measured and are included…".

9. A lot of the work is attempting to get a good handle on the attitude of the spacecraft despite the loss of sensitivity of the star trackers and other ADS efforts. Is there housekeeping information that tells you when different subsystems are on or off to attempt to assess the magnitude of the spacecraft noise? What is the relative magnitude of the residual pointing accuracy error on the final data product compared to your estimate of the spacecraft noise?

Yes there now is a publicly available housekeeping data and plots that shows what instruments were active and at what particular times. There is also a public BUS telemetry file that contains flags for when other various spacecraft subsystems turn on or off as well as the current supplied to them. Both of these are aiding us in our current quest to assess the impact of other spacecraft and instrument subsystems as potential noise sources. However, the current dominant noise source is the reaction wheel tone (Finely et al., 2022). Once the wheels are mitigated we expect to be able to characterize and remove the stray fields resulting from various supply currents in the spacecraft.

We have added text to address this point on lines 329-334 it reads:

". The housekeeping data from the BUS telemetry files will be used to identify when the various spacecraft subsystems turn on or off in an attempt to identify them as potential noise sources. However, the current dominant noise source is the reaction wheel tone (Finley et al., 2022). Once the wheels are mitigated for data prior to the first reaction wheel failure, we expect to be able to characterize and remove the stray fields resulting from various supply currents in the spacecraft and include those results in the next data release"

10. Line 192: "…important than the quantity" (than instead of that)

    That line now reads:

    "We have found that the quality of data selected to derive the in-situ calibrations is generally more important than the quantity of data."

11. Line 208: What is the effect of saturation of the sensor heads in terms of calibration? Was this a big effect initially (compared to the ground-calibration values), but once sensors were repeatedly permed up on orbit, minimal effect? (From Table 1 there seems to be essentially no impact on Gain.).

    Our use of the word 'saturation' was unfortunately misleading. The toward analog path is clipped by the stray field from the magnetorquers (Wallis, 2010). The MAG's offsetting design has a limited instantaneous bandwidth which is temporarily clipped when the magnetorquers suddenly generate a 6000 nT step at 1m as the magnetic feedback cannot slew fast enough to compensate. We have updated the text to reflect this. It now reads:

    "From the Bus telemetry files we flag any data where the magnetotorquers were engaged as they suddenly produce a 6000 nT step of stray field on axis at 1 m (Wallis, 2010) which exceeds the bandwidth of MGF, rendering the data clipped and unusable."

12. Table 1: Though having a large stray field from the boom makes sense since the large X offset is seen in the outboard sensor and not the inboard, what is the boom made from that could give such a

large field? It would be of interest to see the pre-flight off-set values to get a sense of the combination of the spacecraft fields and off-set drift combined.

Compared to the preflight zeros, the offsets found in-situ are significantly larger and are not consistent with a decaying stray dipole field from the spacecraft. The in-situ offsets are also quite stable with time so they do not seem attributable to instrument aging. The boom is primarily carbon fiber with non-magnetic fasteners. However, there is a survival heater that was placed near the outboard end of the boom during integration, which is a potential culprit despite being un-powered. This is especially unfortunate because the offset is so large, it results in a proportionally larger rms error for the outboard sensor. When the reaction wheel tone is removed, the rms error for the outboard sensor is consistently larger than inboard.

We have added the pre-flight zeros to Table 1 along with text on lines 254-259 explaining how and why they are different from the offsets. It reads:

"The calculated pre-flight zeros (Wallis, 2010) are included for completeness. However, it should be noted that these zeros are not the same as the offsets calculated as part of the in-situ calibration as they only represent the intrinsic zero-offsets of the sensor and electronics and do not include effects from stray field from the as it was not possible to quantify those prior to integration. The large offset in b_1 for the outboard sensor is likely due to a magnetized object on the boom near the sensor – the survival heater added to the boom during final integration is a potential candidate."

Additionally, the description for Table 1 was updated and the following lines were added:

"The pre-flight values marked with '' represent the instrument zeros, or the offsets that would be measured by the magnetometer in zero magnetic field and are not the same as the in-situ offsets which include effects from stray-field from the spacecraft."*

13. Line 250: "taken"

That line now reads:

"This implies that the reaction wheel tone has a significant impact on the calibration results and that steps will need to be taken to mitigate the wheel tone in future data releases and doing so should have a significant impact on the calibration results for the early mission."

14. Figure 5. Is this "all" the data or only Kp<3 and small change in Dst "quiet" data?

We double checked the code for the generated plot and noticed that it did not include the Kp and Dst flags as those are normally kept separate from the finished product. We have corrected this and updated Figure 5.

15. Line 279: "….in in-situ…"

    That line now reads:

    "…legitimate changes in in-situ geophysical field.".

16. Was the inboard and outboard sensor used in a "Ness"-type gradiometer way to remove any spacecraft noise? If not, why not?

    Not currently. Ness-style gradiometer removal was intended as part of the mission design; however, it was found to exacerbate the already significant reaction wheel tone – suggesting that the sensors are in the near-field of the wheel tone where a simple dipole approximation is insufficient.

    We have tested different algorithms, two of which (simple differencing and a notch filter) were not magnitude persevering or had difficulty adapting to changing wheel rates. There is a paper now in pre-print detailing the use of Multi-Channel Single Spectrum Analysis (M-SSA) at https://www.essoar.org/doi/abs/10.1002/essoar.10511290.1 *. This has shown very promising results.*

    The use of a Ness-style gradiometer will be revisited once the reaction wheel mitigate algorithms (Finley et al., preprint) are operational.

    We have addressed this point in Section 8, and added the corresponding citations to the references.:

    "Looking further ahead, Ness-style gradiometer noise removal was intended as part of the initial mission design (Wallis, 2015); however, it was found to exacerbate the already significant reaction wheel tone. Once the wheel removal algorithms are operational (Finely et al., 2022), we hope to revisit using this as a potential method of noise removal."

17. Figure 6. What are the red and blue traces in panel b?

    The red and blue traces represent the cross-track measurements from Swarm-A and Swarm-C which passed through the same region of interest at a different time, which is useful from a scientific perspective. Those were not included in the recreation as the main goal was to show the change in the e-POP measurements. As a follow-up, it will be interesting to revisit the analysis done in the original paper and see what if anything has changed with the recent calibration and attitude updates.

    We added a note about the Traces in the description for Figure 6 it reads:

    "The red and blue traces in b) show the cross-track magnetic field for Swarm A and Swarm C respectively reproduced from the original publication."

18. A wild idea not necessarily to pursue for this study (following on the “conjunction” idea in a statistical sense given above), is to use the other SWARM satellites to determine the magnetic equator (when the field is horizontal) and compare locations of Echo with the other SWARM for different 7 day intervals. The poles do shift and move over months/years, but the equator should be pretty “fixed” over multiple 7 day intervals allowing for Echo to pass over the same longitude sector. The offset in location potentially can be used to estimate “off-set” in angle using the CHAOS field line mapping.

    This does seem like an interesting idea to try in future work. In the immediate future, we’re working to remove time-varying local field (observable from the difference between the inboard and outboard sensors) and minimizing our residuals to the limit of the Chaos magnetic field model as discussed in point 3.