1 Detailed Reply to the Comments from Reviewer 1

The mentioned Lines refer to the lines of the manuscript with the comments.

1. Line 7: In a scalar magnetometer, all inaccuracies are deviations of the magnetic field strength measurement from the ambient field strength. Clarify that you are focusing on those effects of intrinsic angular variation due to the physics of your magnetometer operation. As oppose to, for example, interference effects.
   Reply: Clarification added to the abstract.

2. Line 10: is the performance requirement precision or accuracy? What sample rate? Does this include improvements by any calibration or post processing?
   Reply: The performance requirement is the accuracy of 0.2 nT (1-σ) with a sample rate of 1 Hz. No further calibration but post processing in case ratings B, C or D.

3. Line 15: later this is called a requirement. Verifying a requirement vs designing to a target are different motivations and signal different methodologies. To me this paper reads more like requirements verification
   Reply: Sentence removed of the updated manuscript for more clarity.

4. Line 26: It is worth mentioning that thermally induced offset drifts can also be modeled and either compensated or calibrated for. This is mentioned in the Merayo et al. 2000 paper.
   Reply: Annotation added to the new manuscript at line 28.

5. Line 27: This is an important point. Include a citation justifying this point or explain the relative dynamics of the Ganymede magnetic field as it relates to satellite operations.
   Reply: References added to the new manuscript at lines 29-31.

6. Line 34: Explain how
   Reply: Comment added to the new manuscript at line 40 and 41 including reference: A MAGSCA accuracy (0.2 nT) will permit calibration of the magnetic field vector data from the fluxgates to an accuracy sufficient to resolve the higher order moments of Ganymede's dynamo field as well as the 10.5 h, 171.7 h and 27 day induction signals from Ganymede's ocean.

7. Line 35: add citation
   Reply: This information is based on the J-MAG team's internal simulations. There is no citation available.

8. Line 36: Include some justification for why this requirement was set, or at least provide a reference where it is discussed
   Reply: See comment for Line 34.

9. Line 37: Explain the context of this requirement here. Does averaging over many measurements improve error? Does that still meet the 1-sigma requirements? Is there calibration or post-processing applied?
   Reply: The context of the requirement is already explained in the reply to comment for Line 34.

10. Line 57: A diagram of how the instrument is constructed around the gas cell would be helpful (or a citation to one)
    Reply: Reference (Ellmeier et al., 2023) shows a schematic diagram of the sensor unit. This is added in line 94 of the new manuscript.

11. Line 61: is this the difference of the frequencies of the two systems? or is "difference frequency" a term.
    Reply: Reworded to: "The magnetic field strength is derived from the difference of the resonance frequencies of a set of coupled CPT resonances ..." at the line 65 of the new manuscript.

12. Line 63: This is confusing. Do you mean that the consequence is a linear relationship between the measured frequency and magnetic field strength?
    Reply: Yes. This section between the lines 65 and 74 of the new manuscript were adapted for more clarity. Also, Fig. 2 was updated. Now the resonance frequencies of the CPT resonances are added.

13. Line 64: if derived, explain how. If taken from another source provide clear citation
    Reply: See previous reply.

14. Line 70: Is this effect included in your proposed accuracy requirement?
    Reply: If there would be one – luckily there is none – it would have to be included. Sentence removed in new manuscript.

15. Figure 2: You've explained why different resonances are required for different sensor angles, but why do the boxes also imply a range of heading characteristics? By my reading of this figure, heading characteristic is the independent variable of the line plots across sensor angle.
    Reply: The boxes do not imply a range of heading characteristics in the "y" axis of the plot. The boxes are indented to show that in the angular region where two boxes overlap, a magnetometer operation at one or the other resonance is possible. MAGSCA is just configured to switch at the sensor angles of 60°, 120°, 240° and 300°.

16. Line 80: Does this difference in design result in a different calibration procedure? You state in the abstract that your post processing is novel but you haven't made it clear why this post processing wasn't developed for the earlier iterations of this magnetometer technology.
    Reply: This coil system was specifically installed for the investigations of the MAGSCA performance and thus, it was not available for the CSES mission. In lines 80 to 86 of the new manuscript it is now mentioned that

the magnetometer for the CSES-1 mission was tested at another facility where it was compared to a Caesium magnetometer.

17. Line 87: is this referring to the measured magnetic field strength?
Reply: Yes. Sentence reworded in the new manuscript at line 112.

18. Line 89: standard deviation over what? Measurement to measurement? At a characteristic time scale?
Reply: Lines between 113 and 118 reworded for clarity.

19. Line 91: but given the deviations observed in Figure 2, this is not necessary for your required accuracy of 0.2 nT as long as you select the correct resonance
Reply: For the heading characteristic of figure 2, a correction of the heading characteristics is not necessary to achieve an accuracy below 0.2 nT. However, to get the most accurate measurement - even below 0.2 nT - the correction would be necessary. This statement was removed from the new manuscript for clarification.

20. Line 92: And in the conclusion you report that you do not need to correct for heading characteristics
Reply: Statement was removed from the new manuscript for clarification.

21. Line 99: which optical components? and what material are they made of?
Reply: Especially the optical fibres, reference added at line 126 of the new manuscript.

22. Line 100: what level of attenuation is expected. Is the laser bias operation sufficient to overcome this attenuation?
Reply: Based on radiation analysis and test, the - in the worst case - transmitted optical power at the end of the mission lifetime will be reduced to about 1/4 of the initially transmitted optical power. With a higher laser bias current and a sensor temperature, the operation of MAGSCA is possible when an attenuation to 1/4 of the initial optical power (before entering the vapour cell) is introduced. Annotation added to the new manuscript at lines 127 to 130.

23. Line 115: this is going to depend on sampling method. Are you assuming even sampling of angular space?
Reply: Yes, for the presented measurements of the heading characteristics the sensor angles are evenly sampled with 15° (MAGSCA stand alone setup) or 30° steps (J-MAG integrated setup). This information is added to the lines 244 and 251 of the new document.

24. Line 116: where did the error bars on the points in Figure 2 come from, if not from the angular averaged precision? (aka standard deviation)
Reply: Section 4 discusses that for the heading characteristics of Fig. 2, 3 and 4, each data point is the mean value of four separate measurements of the heading characteristics at four different sensor orientations, but with

the same operational parameters and the error bars are the corresponding standard deviations. This information is clarified at the lines 102 to 107 of the new manuscript.
The angular averaged precision is the standard deviation of all data points (magnetic field strength measurements at different, equally spaced sensor angles) of a heading characteristic and thus, it is not depicted in Fig. 2, 3 and 4.

25. Line 119: This is a big assumption. Spacecraft do not tend to evenly sample angular space unless specifically operated to do so. Is this the case? If not, state this clearly as an assumption
Reply: Added to new manuscript at the lines 150 and 151 for clarification: ... achievable during the Ganymede phase of the mission. The primary operational phase of MAGSCA is during the Ganymede phase of the mission. The stated assumption relates to this Ganymede phase.

26. Line 124: This rating of A,B,C,D could be removed. The critical point is that different combinations of angular averaged AE and P require different kinds of post processing. This would be more clearly indicated with a new "necessary post processing" column in Table 1
Reply: Column added to Table 1.

27. Line 124: I see now that you also use this rating system in Table 5 and the conclusion. If you choose to keep the A,B,C,D rating structure, you should at least motivate it by saying that a contribution of this work is to determine what type of a signal post processing may be needed for different operating modes. Than A,B,C,D becomes "post processing types" not just an arbitrary letter grade.
Reply: Comment added to new manuscript at line 154 and 155.

28. Figure 4: As in earlier figure, it's not clear what these error bars represent
Reply: See reply to Line 116.

29. Line 135: to what level? Provide a citation or measurement justifying this claim
Reply: More information concerning the observatory added within the manuscript including a reference at lines 171 to 174 of the manuscript.

30. Line 150: Merritt coil systems also do have a small residual inhomogeneity, is this what you mean?
Reply: Yes. Clarification added to the new manuscript at line 188.

31. Table 2: what sensor? Do you expect the fluxgate sensor repeatability to be at the level of 0.01 nT like you indicate in this table?
Reply: The engineering model of the DFG-magnetometer developed for the Magnetospheric Multiscale mission was used for the measurements. Reference Russell et al. (2014) added to the manuscript. The 0.01 nT is a result of the mathematical calculation of the inhomogeneity (measured in a +5cm, 0cm -5cm grid) per centimeter.

32. Line 165: is this LSB the dominant source of current uncertainty?
Reply: Yes.

33. Line 169: Why is this? It seems like an important part of accuracy verification.
Reply: The accuracy verification was carried out in the x-y-plane of the Merritt coil system to ensure easy rotation and alignment of the sensor. Therefore, no additional test fields were applied in the Z-direction. Annotation added to the new manuscript at the lines 204 to 206.

34. Line 178: what sample rate? or how many total samples?
Reply: The sampling rate was 128 Hz for all measurements presented in the manuscript. Sampling rate was added at line 102 of the new manuscript.

35. Line 198: Include photos or diagrams of both setups
Reply: For the J-MAG integrated setup, the fluxgate sensors were placed outside of the Merritt coil system. Thus, for both setups, only the MAGSCA sensor was inside of the Merritt coil system. The front-end electronics box (for both setups) was located in a distance of more than 7m to the Merritt coil system to prevent any interference. Comments added at lines 252 and 253 of the new manuscript. Change of word "within" to "with" in manuscript at line 235 to avoid confusion.

36. Figure 6. I think this is the MAGSCA stand-alone setup, but this should be clarified
Reply: See previous reply.

37. Line 206: How far away is the MAGSCA front-end electronics in this test? Is there any possibility of interference from the control electronics?
Reply: See reply for Line 198.

38. Equation 7: This equation is confusing and/or the parameters need to be more clearly defined. If a_X is the field along the coil x axis caused by the x coil, and b_Y is the field along the coil x axis caused by the y coil, then both a_X and b_Y in $B_{app}(X)$ should be multiplied by $cos(\beta)$
Reply: For $\beta = 0$ a magnetic field is only applied in the x-axis. No field is applied in the y-axis. Thus, the impact of the coil pointing in the y-axis is 0 in the x-direction, which is satisfied by $\sin(\beta)$. b_Y describes the impact of a magnetic field applied with the Y-axis coils in the Y-direction.

39. Equation 8: you previously defined this residual vector as B_res, why not just make this a vector equation of B_res? (Otherwise at least make it clear that B_x B_y B_z are components of B_{res})
Reply: Equation 8 is rearranged in the manuscript. $B_{res} = (B_x, B_y, B_z)$ added at line 285 for clarity.

40. Line 248: A general weakness of non-linear fitting to scalar measurements is the risk of overfitting if fit functions contain linearly dependent unknown

parameters. You manage to avoid this with the orthogonal functions of β multiplied by k1 through k5 in equation 15. This merits some discussion. Similarly, eqs 10-14 contain 4 unknowns by count, so you can likely solve given the k_i for $i = 1 : 5$. this should also be mentioned. Presumably you are aware of this and this is why you took the steps to reduce the number of fit parameters; you can motivate this section with this point.
Reply: Yes, you are right. We are aware of that and therefore, we reduced the number of fit parameters. To point this out, annotations were added to the new manuscript at the lines 304 to 306.

41. Line 249: how do you know this?
Reply: This is known from measurements with the fluxgate used for measurements of the inhomogeneity. See reply for Table 2.

42. Line 269: Again these parameters need to be more clearly explained. By my reading, b_X and b_Y are the cross-coupling of fields from coils into the orthogonal sensor direction, and therefore are not necessarily equal
Reply: See reply to Equation 7. Both, b_X and b_Y describe the effect of the non-orthogonality between the X- and Y- coils and must therefore be identical.

43. Line 279: How did you achieve exactly 90° rotation? Do you know the expected misalignment of your sensor positioning? Will this contribute to any errors in your fitting?
Reply: This is addressed in the latest version of the manuscript at lines 326 to 332.

44. Line 315: Any magnetically soft material in the sensor can be remagnetized by the applied magnetic field and therefore may depend on applied magnetic field strength. Additionally, magnetic material properties in general do change with temperature. This assumption needs further justification. The addition of an earlier discussion of the materials in the sensor unit may suffice
Reply: The sensor materials are addressed in the new manuscript at line 95.

45. Line 324: Needs further explanation. What uncertainty are you referring to? Which parameter in particular is uncertain?
Reply: The uncertainty introduced by the fitting of the data. Clarification added at line 374 of the new manuscript.

46. Line 333: What might explain this deviation?
Reply: The temperature within in tunnel is about 6°C all year. When a magnetic field is applied to the Merritt coil system for the compensation of the Earth's magnetic field (electric currents in the range of about 3 A for the vertical - Z-axis - component) it takes some time (usually 6 h) until the coil system is in thermal equilibrium. The reported deviation

was (most likely) caused by a too early start of the measurements before the thermal equilibrium of the Merritt coil system was reached.

47. Line 340: Also mention that this figure confirms your point that errors are dominated by heading characteristics
    Reply: In line 77 of the new manuscript we mention that the heading characteristics define the absolute error of the instrument.

48. Line 343: do you have the ability to control the vapour cell temperature in flight?
    Reply: Yes.

49. Line 344: in addition to what? It doesn't seem like any correction at all is needed
    Reply: "Additional" removed

50. Line 349: Is there a proposed explanation for this?
    Reply: A higher laser bias current has a negative effect on the accuracy and precision which can be explained by larger light shift effects due to the higher light intensity within the vapour cell. Reference added.

51. Line 359: Word removed
    Reply: Word removed

52. Line 363: Tie this to the motivation for this work. What does this mean for the JUICE mission, how it will be operated, and how the data will be processed?
    Reply: Annotation added at line 421 of the new manuscript, that the operational parameters (vapour temperature of 25°C and laser bias current of 2.14 mA) were defined as the default configuration of MAGSCA.

53. Line 366: You observed variation in instrument performance at different laser bias currents, but is this difference due to the laser power output or due to the illumination of the gas cell? i.e. if you get radiation darkening of the fiber and increase the laser current to compensate, how do you know you won't see performance similar to the lower current mode pre-darkening?
    Reply: The comment is correct. The heading characteristics are mainly caused by the light intensity within the vapour cell. The coupled CPT resonance amplitude is an indicator for the effective light intensity within the cell. Currently, we plan to utilise the resonance amplitude (already characterised right after launch during the JUICE commissioning) for tracking the radiation induced darkening.

54. Line 369: at least in the environmental and operational conditions you tested. This does not necessarily guarantee that this is true in all cases.
    Reply: Annotation added to line 425.

55. Data availability: Will the fitting software be made similarly available?
    Reply: Remark added to manuscript.

56. References: doi text is correct but hyperlink is broken
    Reply: Should be working now.