AC AND TRANSIENT MAGNETIC EMISSIONS OF THE JUICE GANYMEDE LASER ALTIMETER

R. Kallenbach[(1)], T. Behnke[(1)], S. Engelke[(2)], K. Bubeck[(2)], R. Henkelmann[(3)]

[(1)]*DLR Institute for Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany,*
Email: Reinald.Kallenbach@dlr.de & Thomas.Behnke@dlr.de,
[(2)]*Airbus Defence and Space, 88090 Immenstaad, Germany,*
Email: Stefan.Engelke@airbus.com & Klaus.Bubeck@airbus.com,
[(3)]*Hensoldt Optronics,* Carl-Zeiss-Str. 22, *73447 Oberkochen, Germany,*
Email: reiner.henkelmann@hensoldt.net

ABSTRACT

We report here on qualification and calibration test results constraining the AC magnetic emissions of the JUICE Ganymede Laser Altimeter (GALA) in the frequency range from 0.1 Hz to 50 kHz. The GALA instrument is intended to be launched in 2023 onboard ESA's JUICE spacecraft. It shall map the planetary surfaces of the Jovian moons Europa, Callisto, and Ganymede. The highest AC magnetic emissions are generated at the pulse repetition frequency of 30 Hz and their harmonics by the pump diode laser current pulses with an amplitude of 200 A and a width of 50 to 60 µs and by the load currents of the capacitor reservoirs that drive these current pulses. Additional signatures arise from currents caused by software processes.

1. THE GALA INSTRUMENT

Fig. 1 gives a schematic overview of the GALA Transceiver Unit (TRU). A diode-laser pumped Nd:YAG laser emits pulses at 1064 nm wavelength with nominally 17 mJ energy (9×10^{16} photons) and 5 ns duration at repetition rates of 10 to 30 Hz, and during fly-bys, at reduced pulse energy, up to 50 Hz. The receiver (RX) telescope has an area of 0.05 m^2 and collects a small fraction of these photons scattered off Ganymede's surface, which has a diffuse reflectivity in the range of 0.3 to 0.7. Assuming a nominal spacecraft altitude of 500 km, and an overall RX transmission of 0.8, typically 1000 photons are transmitted onto the Si Avalanche Photodiode detector (APD) which yields, with a nominal responsivity of 685 kV/W and a typical return pulse width of 30 ns, signals of about 6 nW, respectively 4 mV amplitude. The noise spectral density of the sensor is about 12 nV/√Hz in a bandwidth of 100 MHz which gives 0.12 mV rms noise.

The first challenge of the GALA project was the reduction of electro-magnetic interference between the high-power transmitter electronics and the sensitive RX electronics [2]. The second challenge was the reduction of electro-magnetic emissions towards the JUICE spacecraft environment. This is the topic of this article.

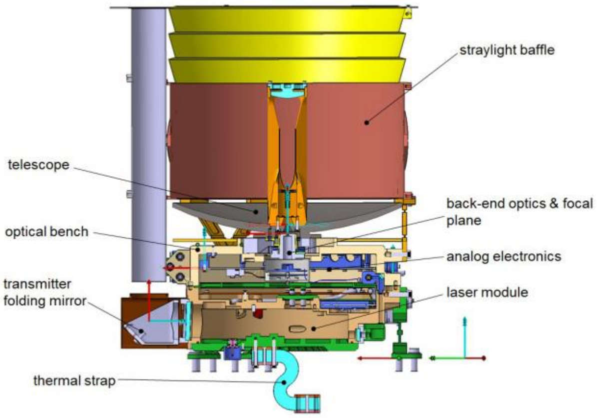

Figure 1. Schematics of the GALA TRU [1]. (Courtesy: DLR/Hensoldt Optronics/JAXA).

2. AC MAGNETIC MOMENTS OF GALA

The unit level requirement for GALA has been posed in the Experiment Interface Document A (EIDA-R0013716) as shown in Fig. 2.

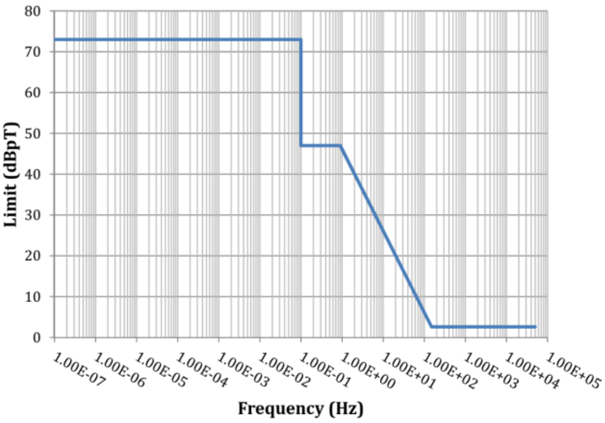

Figure 2. Unit level requirement at 1 m distance.

Low-frequency magnetic fields are usually generated by current loops forming a magnetic moment **m** in units of Am^2, i.e. the current multiplied by the enclosed area. The respective magnetic dipole field scales with the third power of the inverse distance |**r**| from the current loop and dominates at distances large compared to the dimensions of the current loop,

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} \frac{3\boldsymbol{n}(\boldsymbol{n}\cdot\boldsymbol{m}) - \boldsymbol{m}}{|\boldsymbol{r}|^3} \quad (1),$$

where **n** is the unit vector in direction of the vector **r**.

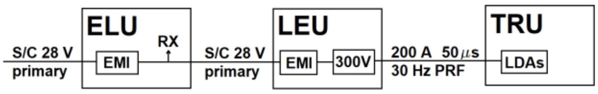

Figure 3. Schematics of GALA high-power circuitry.

Inside GALA, the largest magnetic moments are created by the circuits carrying the highest power (Fig. 3). Firstly, this is the primary 28 V S/C power circuit which extends from the Electronics Unit (ELU) into the Laser Electronics Unit (LEU). It contains a number of common-mode and differential-mode EMI filters. GALA consumes about 1.6 A up to 2 A at end-of-life. Secondly, it is the circuit of the capacitor reservoir charged-up to 300 V to supply the 200 A pump current pulses for the Laser Diode Assemblies (LDAs) lasting 50 µs and repeating usually with 30 Hz frequency.

Setting 10 pT emissions at a distance of 1 m as a bench mark, the current loop area for the 2 A circuit needs to be smaller than 0.25 cm^2, that for the 200 A circuit smaller than 1.5 cm^2 which already includes the duty cycle of 0.15% of the 200 A pulsing.

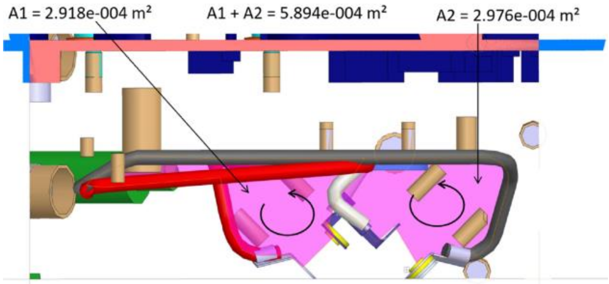

Figure 4. Cable routing near the GALA Laser Diode Assemblies supplied by 200 A pulses.

Fig. 4 shows that it is already challenging to achieve such small loop areas. The loop area near the LDAs is already almost 6 cm^2, and this is only one contribution to the total loop area of the 200 A circuit. However, one needs to look at the exact spectral distribution of the AC magnetic emissions in comparison to the detailed requirement shown in Fig. 2.

For the primary 28 V circuit geometrical constraints look even tougher, however, only the common-mode and differential mode distortions as detected in the conducted emission EMC test in time and frequency domain contribute to the AC magnetic emissions.

3. TEST SETUP

Fig. 5 shows the proto-flight model of the GALA instrument on the wooden bench in the EMC laboratory at Hensoldt Optronics in Oberkochen, Germany.

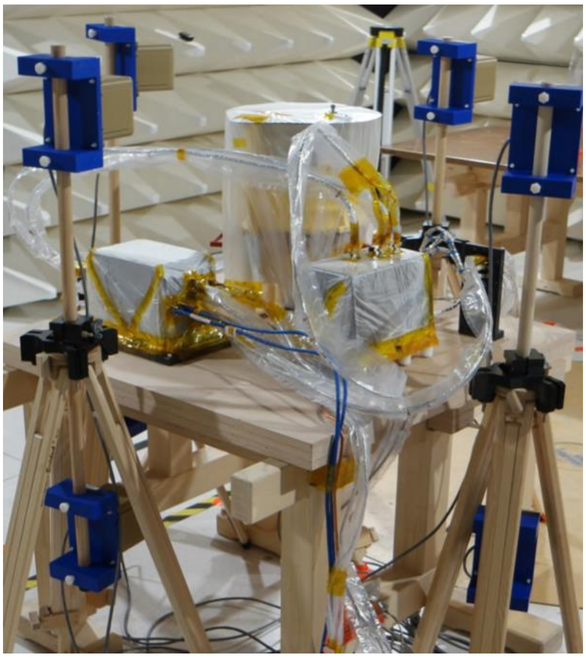

Figure 5. Proto-flight model of the GALA instrument including measurement equipment.
Credit: DLR / Hensoldt Optronics / JAXA / Airbus Defence and Space, Friedrichshafen.

From left to right one can see the Electronics Unit (ELU) including power convertor module (PCM), data processing module (DPM), and the range finder module (RFM), then the TRU, and the Laser Electronics Unit (LEU). At a distance of 0.7 m, the GALA instrument is surrounded by a set of eight search coil magnetometers (SCM) measuring the AC magnetic field in the frequency range from 500 Hz to 50 kHz. In the frequency range 0.1 Hz to 1 kHz, the magnetic field is measured by a set of 14 flux-gate magnetometers (FGMs). The distance of the sensors to the centre of the DUT had to be reduced to 0.7 m in order to achieve the required measurement precision to verify the requirement shown in Fig. 2.

In order to assess the field emissions in the pico-Tesla range, the data processing utilizes a modelled based approach as described in [3]. The signal of the sensors is mapped to time/frequency variant coefficients of a multipole expansion, which is then used to predict the fields at a given distance. The approach enables two key concepts to improve the signal to noise ratio:

(1) Distance scaling: The field as measured by the sensors at a distance of 0.7 m is extrapolated to the distance specified by the requirement at 1.0 m. Thus, the sensor and environmental noise, which leaks into a dipole model is reduced already by a factor of ~3 due to the inverse-cubic distance law. For model coefficients of higher order, the distance law scales even with a higher exponent, leading to an even lower impact of external disturbances.

(2) Signal space separation: For each time sample, the measured field is mapped onto the coefficients of a multi-

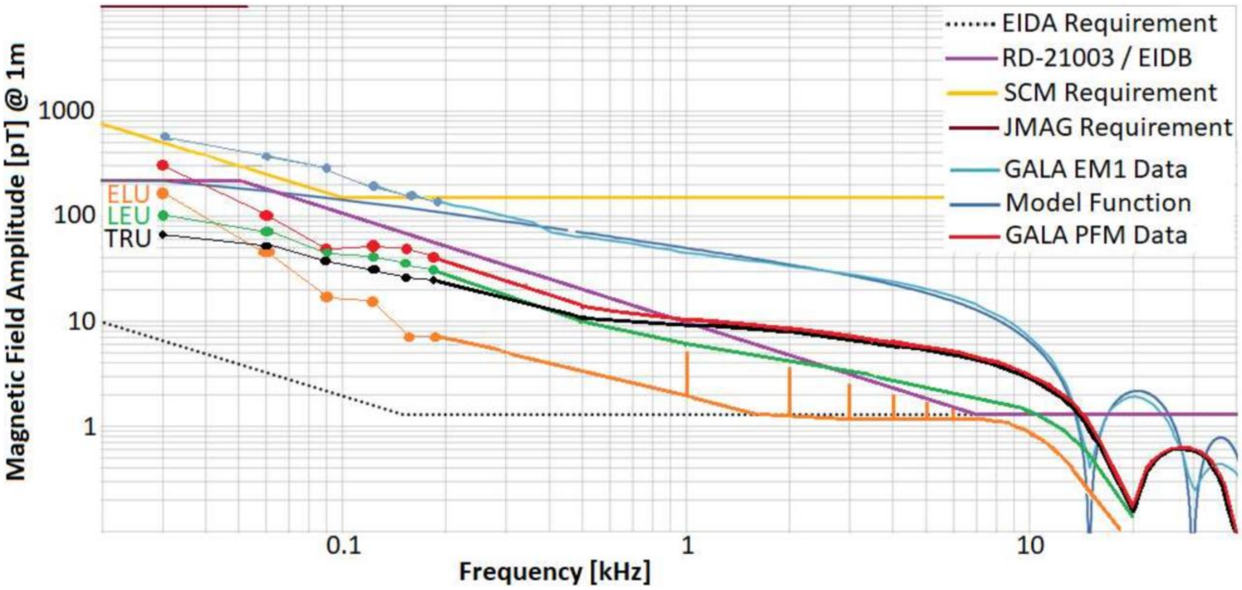

Figure 6. Amplitude spectra for GALA AC magnetic emissions

pole expansion, which models sources up to a given order inside as well as outside of the sensor sphere. The linear independent formulation based on spherical harmonics enables the separation of the two source types in order to dampen the impact of environmental disturbances by rejecting the terms of the outer sources in the subsequent step of field prediction at the distance of requirement specification.

4. TEST RESULTS

The report on test results is split into two parts, one dealing with AC magnetic emissions and one with the quasi-static magnetic fields generated by DC currents inside the GALA instrument. Although the latter magnetic fields are rather DC magnetic fields, their magnitude is determined by an AC measurement at frequencies below 0.1 Hz using the same FGMs as for the AC magnetic emission measurements. The remnant magnetic moments of the non-operational GALA units have also been measured, however, these results are beyond the scope of this paper.

4.1. AC Magnetic Emissions

Fig. 6 shows an overview of measurement data taken with the GALA EM1 model in 2018 at ETS in Noordwijk and with the GALA PFM model in 2020 at Hensoldt facilities. The same measurement equipment, i.e. the same type of FGMs and SCMs, had been used.

Qualitatively, a decrease of the emissions by at least a factor two can be seen from GALA EM1 to GALA PFM. These improvements correspond to redesign activities performed on the EMI filters of GALA as well as on the conductor geometry in the Laser Diode Driver (LDD) board inside the LEU.

The spectra of Fig. 6 represent average amplitudes over a sphere around GALA with a radius of 1 meter. The spectra are dominated by harmonics n x 30 Hz. Above 200 Hz, only the envelopes of the harmonic combs are shown. There is one particular type of emission which has higher amplitude than the envelope of the 30 Hz harmonics: The ELU emits a comb of n x 1 kHz which is related to currents drawn recurrently for software processes (EDAC).

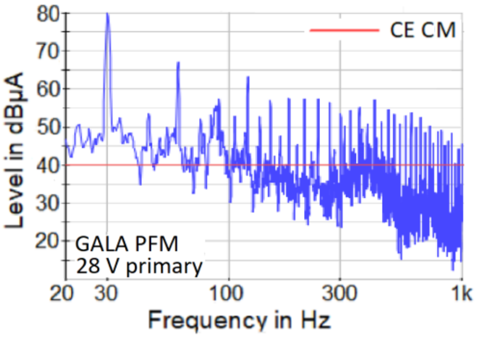

Figure 7. Conducted common-mode emissions of GALA PFM on the S/C primary power line up to 1 kHz.

One can distinguish two characteristic frequency ranges for emission of n x 30 Hz, more distinctly so for the GALA PFM model: AC magnetic emission amplitudes, A_AC (f) (Fig. 6), of the GALA PFM at harmonic frequencies f = n x 30 Hz up to 180 Hz are proportional to the common-mode conducted emission amplitudes, A_CM (f) (Fig. 7), on the primary power line from the S/C to GALA i.e. A_AC (f) / A_CM (f) = (3±1) pT/mA. This means, the AC magnetic emission amplitudes correlate with common-mode conducted emission amplitudes, although the amplitudes themselves vary by a large factor of roughly 10 between 30 Hz and 180 Hz. This suggests that the common-mode current loops of the 28 V S/C power line are the main sources for AC magnetic emissions below 200 Hz. This implies that the S/C grounding environment still may have some effect on the GALA emissions. This is to be verified during the S/C test campaign.

The second signature arises predominantly from the 200 A circuitry to pump the diode lasers with pulses lasting 50 µs at a repetition frequency of 30 Hz. Theoretically a trapezoidal wave form repeating with small duty cycle at some repetition time *T* and current amplitude *A* has the Fourier representation

$$I(f) = \frac{2A\tau}{T} \left|\frac{sin(\pi f \tau)}{\pi f \tau}\right| \left|\frac{sin(\pi f t_r)}{\pi f t_r}\right| [A] \qquad (2),$$

where $\tau = 50$ µs is the current pulse width and t_r the rise and fall time of this pulse. For GALA, we have $t_r \ll \tau$, implying that the spectrum remains close to its amplitude of $2A\tau/T = 0.61$ A up to frequencies of about $f = 2/\tau = 10$ kHz. The first zero-amplitude occurs at $f = 20$ kHz as can be seen in the data of Fig. 6. Note, that for the GALA EM1 a longer pump time of $\tau = 70$ µs had been applied which shifts the "zero" to about 14 kHz.

In the frequency range 1 kHz to 6 kHz we note the following characteristics of the GALA PFM emissions and some deviations from the ideal "trapezoidal" spectrum:

- The emissions are dominated by the TRU emissions and resemble most closely the "trapezoidal" spectrum. The TRU contains conductors of the 200 A pump diode laser circuit only but no primary current paths.
- The emissions at 6 kHz are a factor of 2 lower than at 1 kHz. The ideal "trapezoidal" spectrum should only fall off by about 20%.
- The decrease in amplitude between 1 kHz and 6 kHz is much less than the decrease in common-mode conducted emissions amplitude which is about a factor 30 (Fig. 8) i.e. there is no correlation.

This suggests that the spectrum in the range from 1 kHz to 6 kHz is dominated by the 200 A pulses and not by the common-mode currents of the primary circuit. A damping process seems to be active at frequencies above a few hundred Hz. The scaling for limited penetration into AlBeMet (similar to Aluminum) is given by the skin depth of about 3 mm/sqrt(*f* / 1 kHz). This matches the AC magnetic amplitude scaling as the laser system inside the TRU is enclosed by a few mm of AlBeMet.

The maximum amplitude of the "trapezoidal" emission of the TRU is estimated to 10 pT which corresponds to a loop area of roughly 5 cm^2 for a current amplitude of 0.6 A (see Eqs. 1 & 2). This is the geometrical size of the loop area of the 200 A current path near the LDAs inside the TRU.

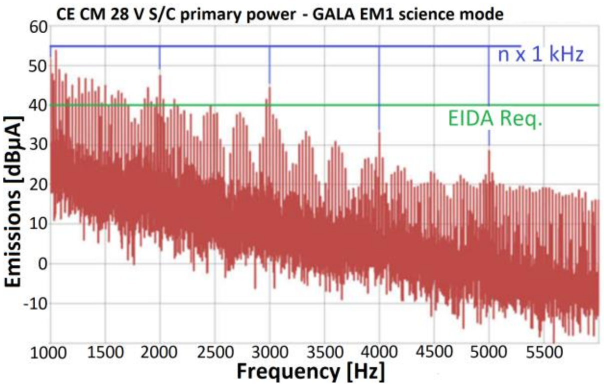

Figure 8. Conducted common-mode emissions of GALA EM1 on the S/C primary power line. The spectrum shows the mixing of n x 30 Hz and n x 1 kHz harmonics. Similar behaviour is seen for the GALA PFM.

There seems to be a damping process active at frequencies above a few hundred Hz. The scaling for limited penetration into AlBeMet is given by the skin depth, which is about 3 mm / sqrt(*f* / 1 kHz). This would match the AC magnetic amplitude scaling considering the fact that within 1 m distance, the TRU is surrounded by a few mm of conducting material such as AlBeMet.

The maximum amplitude of the "trapezoidal" emission of the TRU is estimated to 10 pT which corresponds to a loop area of roughly 5 cm^2 for a current amplitude of 0.6 A (see Eqs. 1 & 2). This is the geometrical size of the loop area of the 200 A current path near the LDAs inside the TRU.

A strong deviation of the AC magnetic emissions in the frequency range from 1 kHz to 20 kHz is observed during operation of the redundant laser. While the main laser emits the typical "trapezoidal spectrum", this seems to be suppressed for the redundant laser (Fig. 9).

This difference cannot be explained by any asymmetry in the structure of the TRU. The surrounding metal structures are almost entirely symmetric. Neither can the difference be explained by the measurement setup because it had been completely identical for the two measurements. This had been supported by calibration measurements in the idle mode of GALA.

Furthermore, the differences cannot be explained by different shapes of the 200 A diode laser pulses. Fig. 9 shows the measurements for the pulse shapes for both the main and the redundant laser system. These shapes are very similar, although not exactly symmetric trapezoids, and could not explain large differences in their Fourier spectra.

It will further be investigated which is the cause of the reduced AC magnetic emissions because this may open the possibility to actively control the energy contained in AC magnetic emissions of a space instrument.

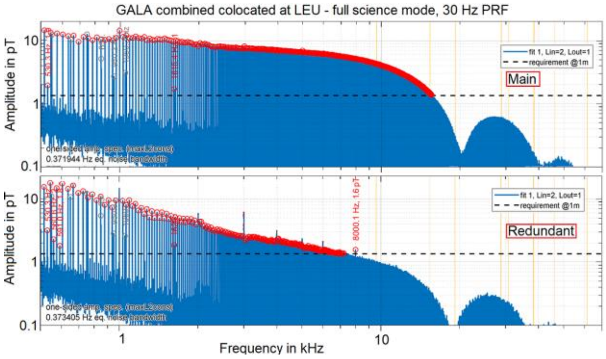

Figure 9. Amplitude spectrum of GALA AC magnetic emissions in the frequency range 500 Hz to 50 kHz while the main laser is active (upper panel) and during operation of the redundant laser system (lower panel). Credit: DLR/Hensoldt Optronics/JAXA/Airbus Defence and Space, Friedrichshafen.

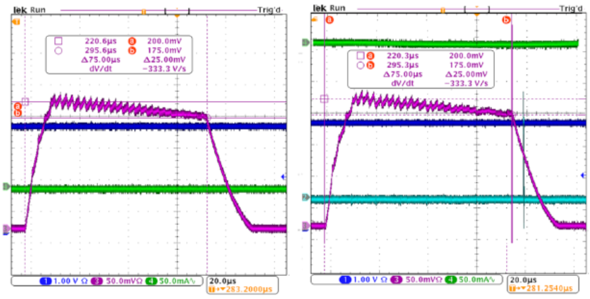

Figure 9. Pulse shapes for the main (left panel) and redundant (right panel) laser diode current pulses.

Most likely, additional damping of the emissions of the redundant laser occurs by electronics components such as transformers or inductances. Very near to the laser systems, the TRU contains the analogue electronics module (AEM) of the RX which has an asymmetric layout regarding the position of power supplies, in particular that of the high voltage applied to the avalanche photodiode. It cannot be proven at the moment that this is indeed the cause. It would require either additional simulations to be contracted to Dassault systems, such as the one shown in Fig. 10, or a careful analysis of higher AC magnetic moments which unfortunately fall off very rapidly with distance from the centre of the instrument.

The nearly trapezoidal 200 A current pulse shapes in Fig. 9 show another detail that is related to the design improvements of the laser diode driver (LDD). The small ripple with a period of 2.5 µs is a signature of switching the 200 A current pulses alternately over four MOSFETs. This is done in order not to violate the current limits of the used MOSFETs but also has to do with the design of the LDD which dynamically divides the voltage of the capacitor reservoir (about 300 V) to the much lower voltage applied to the actual diode lasers. The different geometries of the four current paths originally spanned a rather large area between forward and return currents. This area could be reduced by modified routing.

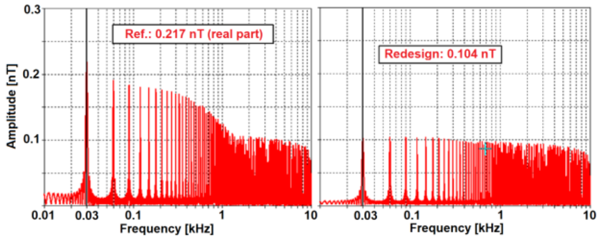

Figure 10. Simulations of AC magnetic emissions of the LDD before redesign (left panel) and after redesign (right panel). Credit: Dassault Systems

In order to optimize the LDD board routing geometry simulations have been performed by Dassault systems. The simulations for the reduction of AC magnetic emissions (Fig. 10) suggest that pre-dominantly the emissions below 1 kHz have been reduced by the redesign of the PFM LDD with respect to the EM1 LDD. Only after this redesign, the statement applies that the emissions at frequencies below 200 Hz are dominated by the common-mode currents of the primary 28 V S/C power circuit. For the EM1, the LDD was the single dominant emitter.

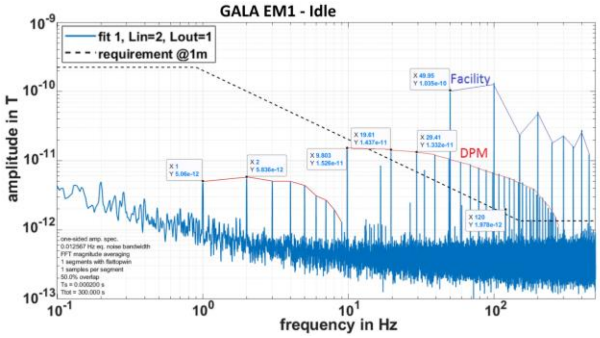

Figure 11. AC magnetic emissions of the GALA EM1 model below 30 Hz. Credit: ETS/ESTEC

Last but not least, it should be mentioned here that software processes in the Data Processing Module (DPM) are not only observed at n x 1 kHz as visible in Figs. 6&8, but also at lower frequencies such as n x 1 Hz or n x 9.8 Hz. They can be traced back to recurrent software cycles and are also observed in conducted emission in internal power lines for both the GALA EM1 and the GALA PFM.

4.2. Quasi-static Magnetic Emissions

Quasi-static magnetic moments have been measured for the GALA PFM instrument while it has been commanded to go through a typical sequence of modes representing the mission scenario. Powering and switching off different electrical circuits change the magnetic moment of GALA and will cause an adjacent change of the magnetic field measured by the JMAG magnetometer onboard JUICE. If these changes are systematic and reproducible, magnetic-field measurements in the Jovian magnetosphere can be corrected accordingly.

The typical sequence of GALA includes Power ON (step 1) which activates the Power Converter Module (PCM) and the Data Processing Module (DPM) inside the ELU, as well as the Laser Control Module (LCM) inside the LEU. The change to science mode (step 2) activates the Rangefinder Module (RFM) inside the ELU and part of the Analogue Electronics Module (AEM) inside the TRU as part of the Receiver. It also activates the load current of the 300 V capacitor reservoir inside the LEU. The next step (3) is activation of laser firing in parallel with switching on the ADCs of the AEM which digitize the APD sensor data. The high voltage of the APD is ramped up within about 2 minutes. Then laser firing is stopped (step 4) while the RX including its ADCs is still ON. Step 5 follows turning off the RFM and AEM, and then step 6 back to idle, finally Power OFF (step 7).

Fig. 12 shows the measurement results during operation of the main and the redundant modules of GALA. Note, that the RFM, the AEM, and the APD sensor do not have redundancy.

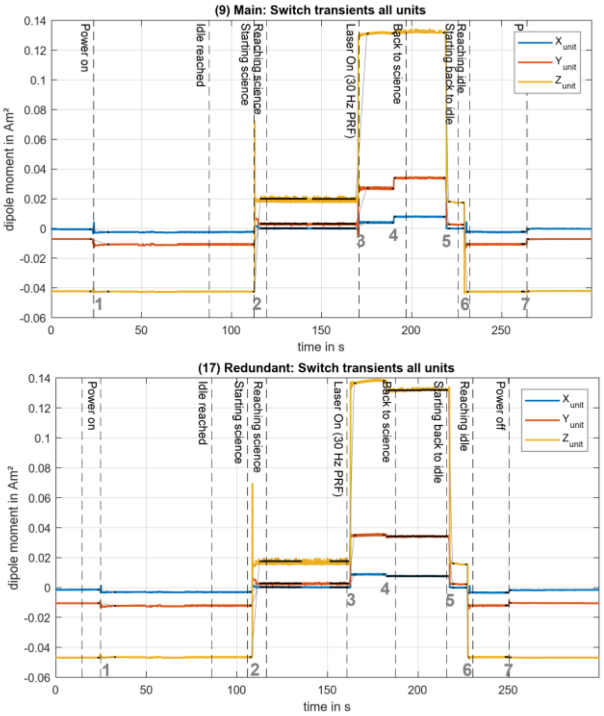

Figure 12. Magnetic moment changes of the GALA PFM instrument during operation of the main and redundant modules.

It turned out that the current powering the ADCs creates a rather large quasi-static magnetic moment comparable to the magnetic moments caused by the laser system. The total quasi-static magnetic field of GALA in full science operation amounts to 38 nT at 1 m distance. Only 4.5 nT are acceptable for JMAG onboard JUICE so that it is important to know that the quasi-static magnetic moments of GALA are reproducible and precisely predictable for each operation mode. In that case JMAG measurements can be corrected for magnetic field generated by GALA.

5. SUMMARY

The AC magnetic emissions of GALA are dominated by three sources:

1) At frequencies below about 200 Hz, the strongest emissions are caused by common-mode currents in the primary 28 V S/C power supply circuit that extends into the two electronic units ELU and LEU of the GALA instrument. These common-mode currents are the fundamental and first few harmonics of the pulse repetition frequency of nominally 30 Hz of the GALA high-power laser.
2) At frequencies above 200 Hz, the harmonic comb n x 30 Hz of the 200 A diode laser current pulses with a width of 50 µs dominate.
3) At special frequencies such as n x 1 Hz, n x 9.8 Hz, and n x 1 kHz, the currents caused by software cycles dominate. These current spikes are also observed in conducted emissions on the primary and internal power lines of GALA.

An important observation has been made regarding differences in the AC magnetic emissions of the main and the redundant laser system at frequencies from 1 kHz to 10 kHz. These differences are difficult to be explained by an asymmetric environment of conducting materials around the two laser systems, neither can they be traced back to different pulse shapes of the 200 A diode laser pump currents. They may be caused by an asymmetric placement of magnetic components such as transformer coils inside the TRU. However, this cannot be verified without further detailed experiments and/or simulations.

6. REFERENCES

1. H. Hussmann, K. Lingenauber, R. Kallenbach, K. Enya, N. Thomas, L. M. Lara and the GALA team, CEAS Space Journal, 11(4), 381-390, doi:10.1007/s12567-019-00282-8.

2. T. Behnke, M. Fuji, R. Kallenbach, M. Kobayashi, R. Henkelmann, Y. Sato, J. Uhrle, "Laser Ranging signal detection in harsh EMC environment", 2019 ESA Workshop on Aerospace EMC, *IEEE Xplore*, DOI:10.1109/AeroEMC.2016.7504591.

3. C. Trenkel, S. Engelke, K. Bubeck, J. Lange, Z. Tenacci, A. Junge, "Reliable Distance Scaling of AC Magnetic Fields for Space Mission Verification Campaigns", 2019 ESA Workshop on Aerospace EMC, IEEE Xplore, DOI: 10.23919/AeroEMC.2019.8788957