

HIGH FIDELITY SURFACE CHARGING AND MAGNETIC NOISE ANALYSIS OF THE JUNO MAGNETOMETER

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ABSTRACT

During Earth flyby of NASA's Juno spacecraft, unexpected noise was observed in magnetometer data. The noise is attributed to surface currents sourced from ionospheric plasma and directed through the magnetometer boom structure by a $v \times B$ electric field. Approximate hand calculations under-predicted the severity of the noise by an order of magnitude. In response, a high fidelity analysis was performed to assess confidence in our model and risk to magnetometer science at Jupiter. Combining NASCAP2k with commercial FEA software, and using detailed inputs from a variety of environment models and CAD tools, the observed effect at Earth was replicated with agreement to a factor of 2. Extending the model to the Jovian environment, we predict a signal-to-noise ratio that is more favourable than at Earth and acceptable to magnetometer science.

1. INTRODUCTION

NASA's Juno spacecraft is a Jupiter orbiter intended to study the planet's origin and evolution. Among its instruments is a magnetometer mounted on a boom as shown in Figure 1. During Earth flyby in 2013, the magnetometer experienced noise an order of magnitude larger than expected. The source of the noise is thought to be magnetic fields from structure currents sourced from the plasma environment and directed through the magnetometer boom structure by a $v \times B$ electric field. A detailed simulation of the problem, with high-fidelity models of the geometry, environment, and physics, produce results that agree with the Earth measurements to a factor of 2. Extension of the model to the Jovian



Figure 1. Juno Spacecraft;
Magnetometer Boom Circled in Red

environment predicts a signal-to-noise ratio that is acceptable to magnetometer science.

2. OBSERVATIONS AT FLYBY AND EXPLANATION

Juno is spin stabilized and rotating in the plane of its solar arrays at 2 rpm. During Earth flyby, noise in magnetometer data was observed with modulation at the same 2 cycle per minute frequency (Figure 2). The magnitude of modulation was 10nT, resulting in a signal to noise ratio of 2500:1 in Earth's 25 μ T field. Some noise was expected based on approximate calculations made before launch, but the observed magnitude was ten times higher than calculated. At this level, the required accuracy of the magnetometer was threatened.

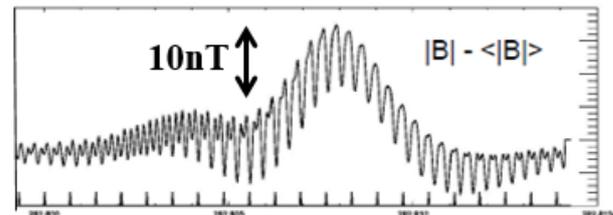


Figure 2 - Magnetometer Data Taken During
Earth Flyby, Showing 10nT Oscillations

The suspected source of noise is structure current running past the magnetometer. This current is collected from the plasma and directed by a $v \times B$ effect such that the current density is high in the magnetometer boom.

The $v \times B$ effect is present in both the Earth and Jupiter environments, and the orientation of the velocity and magnetic field vectors is such that the $v \times B$ electric field lies in the plane of the solar arrays. Because the spacecraft is rotating in the same plane, the $v \times B$ electric field rotates on the structure at 2 rpm (Figure 3). The $v \times B$ electric field periodically forces current flow past the magnetometers, which produces the observed magnetic noise.

The direction of the $v \times B$ electric field vector determines which area of the spacecraft is electron-collecting and which is ion-collecting. Due to the higher mobility of electrons in the plasma, a much larger fraction of the spacecraft surface area is ion-collecting vs. electron-collecting. In the Earth case, electrons are collected on

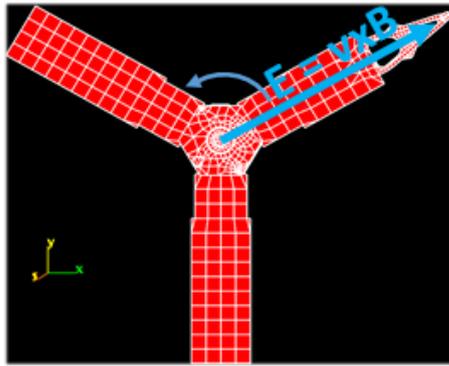


Figure 3 - Mesh of Juno Spacecraft used in NASCAP2k. The $v \times B$ effect in both the Earth and Jupiter Case is nearly in the Plane of the Solar Arrays and is Rotating in that Plane at 2 rpm

only 8% of the surface area (see Figure 4 for a qualitative representation). Total current is conserved, so the same amount of current collected in the 92% ion-collecting area is lost over the small 8% electron-collecting area. This has the effect of producing large structure currents near the electron collecting region and small currents further away. Therefore, when the spacecraft is in the part of its rotation such that the $v \times B$ electric field forces electron collection in the mag boom (as in Figure 4), large magnetic disturbances are seen. However, for the $\sim 2/3$ of each rotation where current is collected on the other solar arrays, as in Figure 5, the magnetic disturbance is low. So, the rotation of the spacecraft combined with the $v \times B$ effect modulates the current density near the magnetometers, and hence the magnetometer noise, at the spacecraft spin rate. The uneven fraction of the rotation spent at high disturbance vs low disturbance can be seen in the spiking nature of the Earth flyby data in Figure 2.

This effect was modelled in the original calculations but various approximations to the geometry and physics led

to an under-prediction of the noise. The discrepancy between the calculated and measured noise generated concern that the model of the problem might be wrong and that similar noise at Jupiter would jeopardize magnetometer science. This prompted the development of a detailed NASCAP2k and ANSYS model.

3. MODELLING THE EFFECT – NASCAP2K AND ANSYS

In order to re-evaluate the problem and better assess risk, a model was created with more detailed environments, spacecraft geometry, and physics. Trajectory information was gathered for Juno at Earth flyby and used as input to the International Reference Ionosphere (IRI) model to refine the plasma properties during Earth flyby. Input to the IRI model is shown in Table 1. The trajectory information was also used to run

Table 1 - Input to IRI Model

Time (UTC):	10/09/2013 19:21:26
Latitude:	-34.23°
W Longitude:	34.05°
Altitude:	561.10 km
Daily Ap index:	29
3-Hour Ap index:	6
81-day F10.7 radio flux:	125.9
Daily 10.7 radio flux:	113.1
IG12 index:	90
Sunspot number Rz12:	74.6

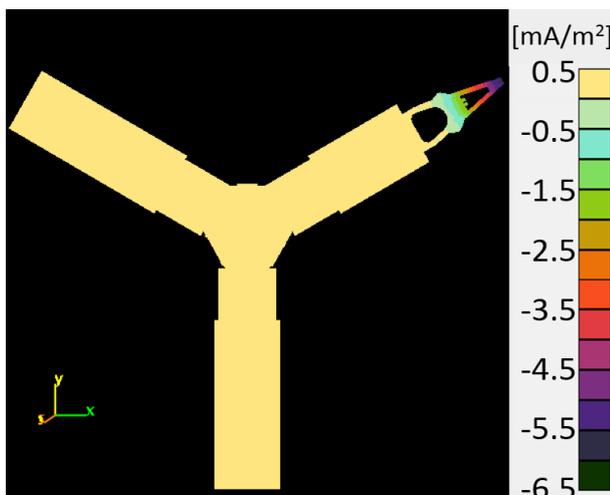


Figure 4 - Surface Charging Current during Earth Flyby. "0 deg orientation"

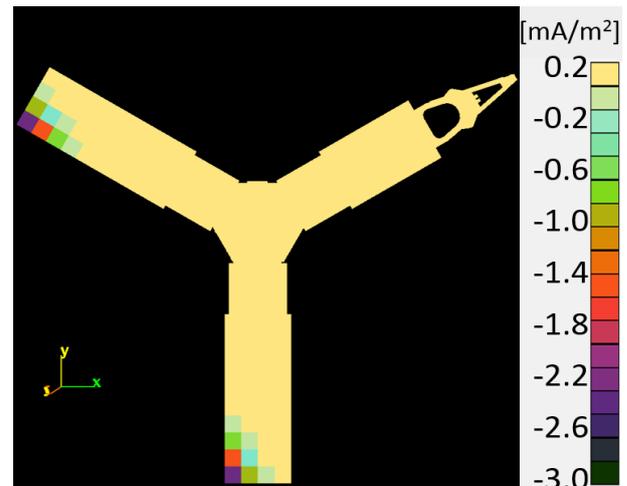


Figure 5 - Surface Charging Current during Earth Flyby. "180 deg orientation"

the International Geomagnetic Reference Field model to get a refined magnetic field vector.

The original calculations had used estimates for various geometric parameters, such as total surface area, ram surface area, magnetometer location, and spacecraft shape. To refine these estimates, a detailed CAD model of the Juno spacecraft was acquired and modified to the appropriate fidelity using various CAD tools. The geometry was then meshed using FEA software for import into NASCAP2k. The final meshed geometry is shown in Figure 3 and a zoomed in view of the magnetometer boom (with a contour plot of the collected current) is shown in Figure 6. The meshed geometry was imported into NASCAP2k, along with the calculated plasma parameters, magnetic field vector, and spacecraft ephemeris and attitude. NASCAP2k calculated the current density to each element on the spacecraft. The results of this simulation are shown in

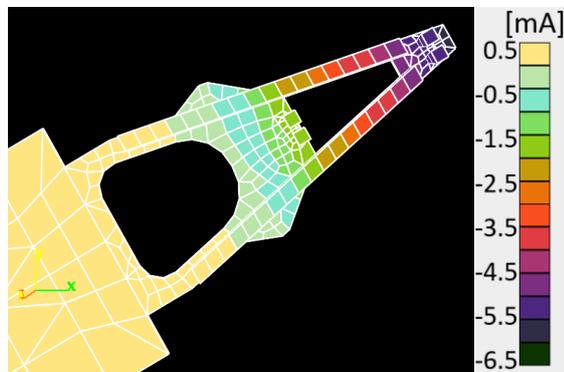


Figure 6 - Surface Charging Current during Earth Flyby, Zoomed to Mag-Boom

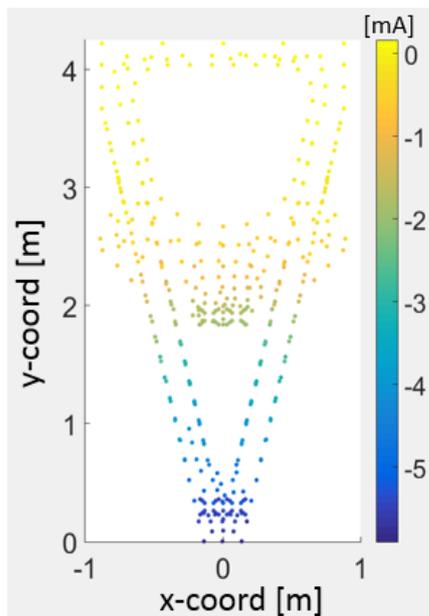


Figure 7 - Matlab Output of Surface Charging Current Density Profile on Mag-Boom, Earth Case

Figures 4, 5, and 6.

This information was exported from NASCAP2k and post-processed in Matlab to isolate just the data in the mag-boom structure. It was also manipulated into a format and coordinate system compatible with our finite element analysis tool, ANSYS. The output of this step is surface current density defined over the space of the mag-boom, and is shown in Figure 7.

The surface current density distribution from Matlab was imported into ANSYS and used to define a boundary current source over the surface of the mag-boom. ANSYS then solves for the resulting current paths in the structure and for the magnetic fields they generate. By probing the magnetic field at the locations of the magnetometers, the expected noise seen from this effect is determined. Graphical output from ANSYS is shown in Figures 8 and 9. The current paths and

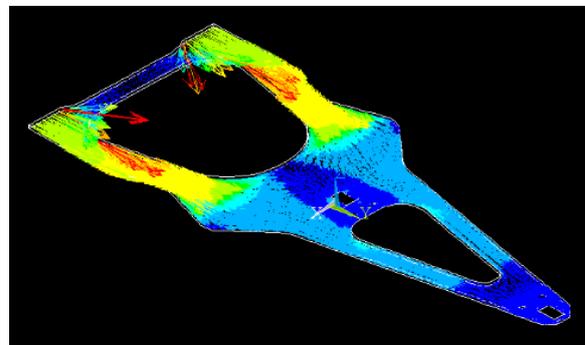


Figure 8 - ANSYS Output; Current Paths Solved for in the Mag-Boom Structure

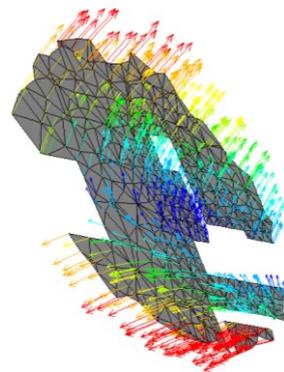


Figure 9 - Magnetic Field Solved for around the Mag-Boom Structure

resulting magnetic fields have been solved for and are depicted as vectors over the space in and around the mag-boom structure. This process was carried out for 26 orientations at 10 degree intervals to get a 260-degree profile of the induced magnetic field. The reason only 260 degrees are covered instead of the full 360 is that for much of the rotation the field is zero and to save time, many of those cases were not run.

4. RESULTS OF EARTH SIMULATION

The results of the simulation at Earth are shown in Figure 10. At the 0-degree orientation (with the vxB electric field aligned with the mag-boom) the magnitude of the induced field is 5nT. As can be seen in Figure 2, the magnitude of the field observed during flyby was 10nT. The simulation agrees with the observation to a factor of 2. In addition, the somewhat jagged shape of the observed waveform corresponds well with the variation of the simulated fields over a 360-degree cycle. And keeping in mind the uncertainty in the plasma environment and the fact that the geometry is still rather simple from a current-path standpoint (no MLI or its ground paths were included), this result gives us confidence that we have an understanding of the source of the noise and the ability to model it.

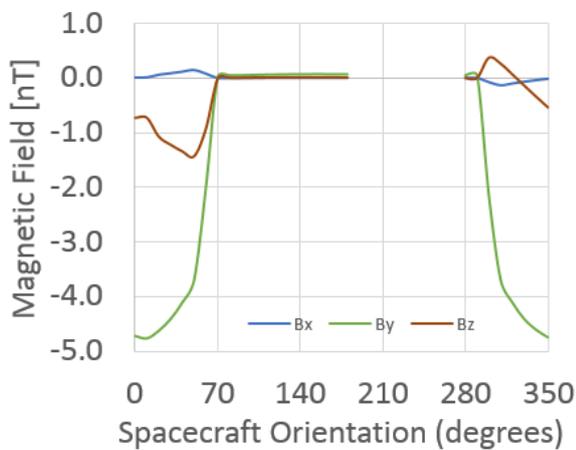


Figure 10 - ANSYS Output of Magnetic Field Components at Inboard Magnetometer. Magnitude is 5nT

5. EXTENDING THE ANALYSIS TO THE JOVIAN ENVIRONMENT

Juno will descend to 3500km above the 1 bar level at Jupiter. At this altitude, the worst case plasma density is $3E10\text{ m}^{-3}$ from Voyager data presented in [2]. This is a less dense plasma than at Earth flyby, but also a more energetic plasma. No data was available for plasma temperature at that altitude, so the worst case plasma temperature was calculated theoretically by Hunter Waite of the South West Research Institute. The resulting worst case temperature was calculated to be 0.86eV, which is higher than the 0.15eV at Earth. The magnetic field at Jupiter was calculated with GIRE2 and is 20 times higher magnitude than at Earth. The spacecraft velocity relative to the plasma is also 4 times higher at Jupiter, resulting in a vxB effect that is 80 times stronger. Again, the orientation of the spacecraft is such that the vxB electric field is rotating nearly in the plane of the solar arrays. Also at Jupiter the spacecraft is sunlit as opposed to eclipsed at Earth, and the ion species in the plasma are mostly Sulfer as

opposed to Oxygen at Earth. The parameters for the models at both Earth and Jupiter are shown in Table 2.

Table 2 - Relevant Parameters to Simulation

Parameter	Units	Earth	Jupiter Worst Case
Electron Density	[m ⁻³]	8.14E+10	3.00E+10
Plasma Temperature	[eV]	0.12	0.86
Debye Length	[cm]	1	4
Dominant Ion Species	-	O+(.98), H+(.02)	S+(.7), O+ (.2), S++(.02), O++(.03)
Sun Intensity (rel to Earth)	-	0	0.04
Juno Velocity: v	[km/s]	14.6	57
Magnetic field: B	[μT]	24.3	540
v X B: vxB	[V/m]	0.35	29
Collected Current	[mA]	16	29
Induced Magnetic Field: B	[nT]	5	10

The surface charging current at Jupiter was calculated using NASCAP2k. Results are shown in Figure 11. More current is collected than at Earth, and the stronger vxB effect forces electron collection further towards the tip of the mag boom compared to the Earth case, resulting in a larger fraction of the maximum collected current passing near the magnetometers.

Running the Jupiter surface charging current distribution through ANSYS, we calculate a peak in noise of 10nT, or about 2 times more noise than at Earth (Figure 12). However, considering that the magnetic field being measured at Jupiter is 20 times stronger, the signal-to-noise ratio instead improves by an order of magnitude at Jupiter. In our simulation, the ratio is 50,000:1.

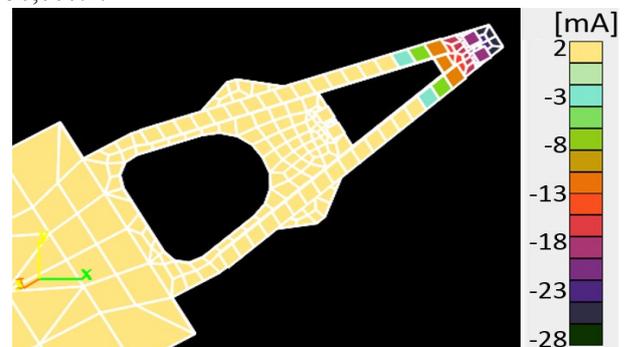


Figure 11 - Surface Charging Current Density at Jupiter

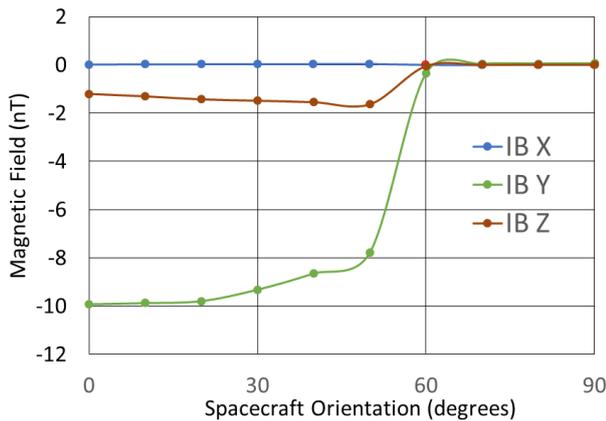


Figure 12 - Induced Magnetic Field at Jupiter.
Magnitude is 10nT

In addition, we know that the magnetometers are relatively undisturbed during the portion of the rotation where electron collection is occurring on other parts of the spacecraft. We therefore know what the undisturbed measurement is for these cases, and it is identifiable because of the non-uniform periodic profile of the noise. The suspected undisturbed magnetic field measurement is highlighted in red in Figure 13.

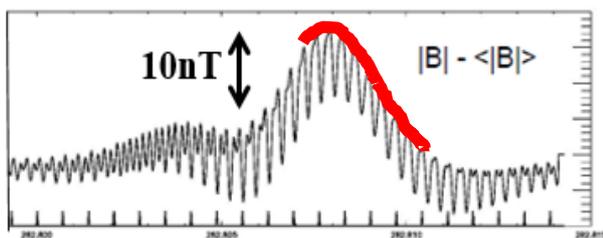


Figure 13 - Magnetometer Data. Undisturbed Data Profile Indicated with Red Line

6. CONCLUSION

The noise observed in magnetometer data appears to be due to structure currents sourced from the plasma environment and directed past the magnetometer by a $v \times B$ effect. The structure currents generate magnetic fields that the magnetometers pick up. A high-fidelity simulation of the problem at Earth flyby was performed using detailed geometry and environment models, NASCAP2k surface charging software, and ANSYS finite element software. The results of the simulation at Earth agree with the measured data to a factor of 2, which is within the uncertainty of the plasma environment. This supports our hypothesis of the source of the noise. Extending the simulation to the Jovian environment, we get results that show a low signal-to-noise ratio that is acceptable to magnetometer science. In addition, by understanding the source of the noise, we know during which portion of the spacecraft's 2rpm rotation the magnetometer is being negligibly affected by structure currents, and we can identify it in the data.

Magnetometer science is not at any significant risk from this effect.

7. ACKNOWLEDGEMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8. REFERENCES

1. Divine, Neil & Garrett, H.B. (1983). Charged Particle Distributions in Jupiter's Magnetosphere, *Journal of Geophysical Research*, Vol. 88, No. A9, Pages 6889-6903.
2. Yelle, R. V., and S. Miller, "Jupiter's Thermosphere and Ionosphere", Chapter 9, pp. 185-218, in *Jupiter, The Planet, Satellites and Magnetosphere*, edited by F. Bagenal, T. Dowling and W. McKinnon, Cambridge Press, Cambridge, UK, 2004.