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

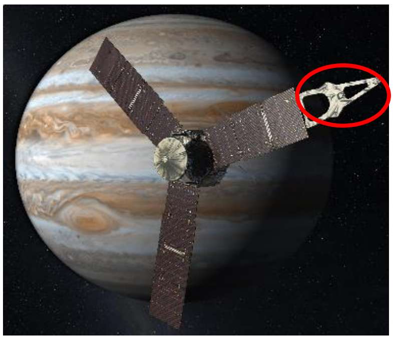


Figure 1. Juno Spacecraft; Magnetometer Boom Circled in Red

2. OBSERVATIONS AT FLYBY AND EXPLANATION

Juno is spin stabilized and rotating in the plane of its solar panels 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, which gives a signal to noise ratio of 2500:1 in Earth's 25µT field. Some noise was expected based on approximate hand calculations made before launch, but the observed level was an order of magnitude higher than the predicted level. This discrepancy was concerning to the science team because it was coming close to infringing on the required accuracy of the magnetometer.

The source of noise is thought to be current collected from the plasma running through the spacecraft structure and generating undesirable magnetic fields near the magnetometer. A vxB effect is present in both the Earth and Jupiter environments, and the orientation of the velocity and magnetic field vectors is such that the vxB electric field lies in the plane of the solar arrays.

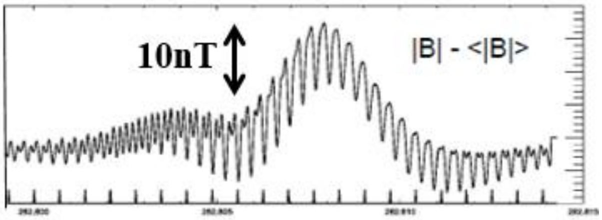


Figure 2 - Magnetometer Data Taken During Earth Flyby, Showing 10nT Oscillations

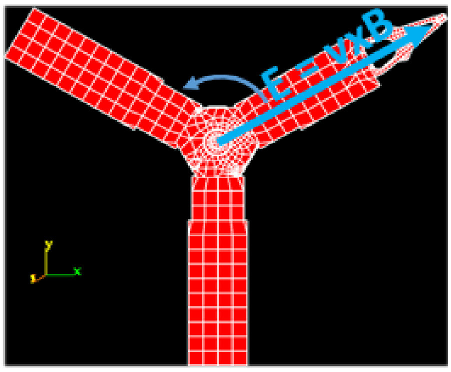


Figure 3 - Mesh of Juno Spacecraft used in NASCAP2k. The vxB effect in both the Earth and Jupiter Case is nearly in the Plane of the Solar Arrays and is Rotating in that Plane at 2 rpm

The resultant electric field periodically forces current flow past the magnetometers, which produces the observed magnetic noise. Because the spacecraft is rotating in the same plane, the vxB electric field rotates like the hand of a clock on the structure at 2 rpm (Figure 3).

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

The original calculations were wary of this effect but various approximations to the geometry and physics led to an under-prediction of the noise. The discrepancy between this prediction and the 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. MODELING 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 Figure 6. The trajectory information was also used to run the International Geomagnetic Reference Field model to get a refined magnetic field vector.

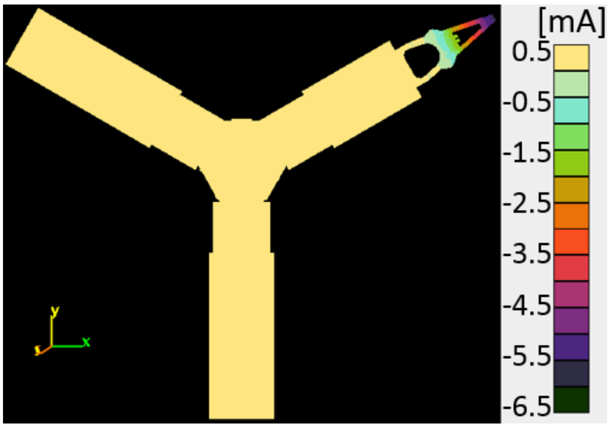


Figure 4 - Surface Charging Current during Earth Flyby. "0 deg orientation"

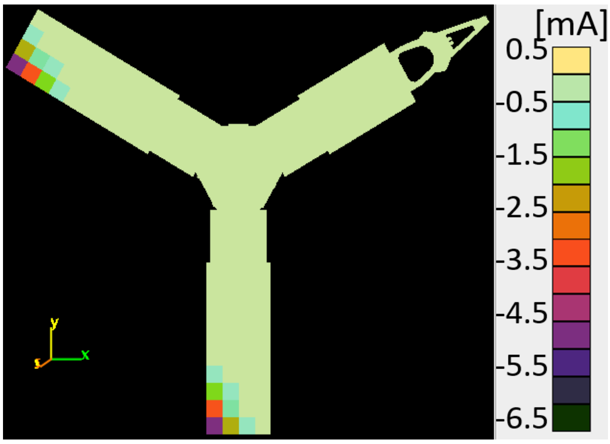
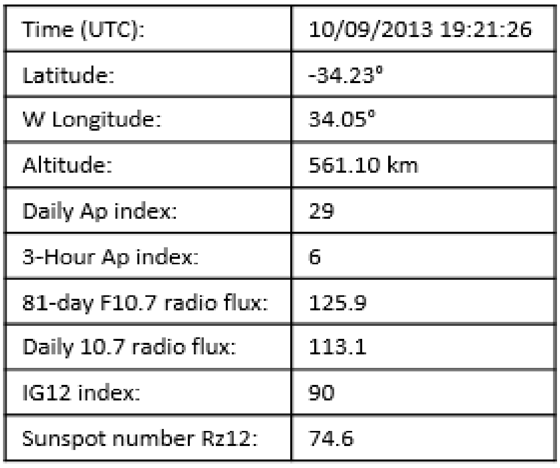


Figure 5 - Surface Charging Current during Earth Flyby. "180 deg orientation"



Time (UTC):	10/09/2013 19:21:26
Latitude:	-34.23°
W Longitude:	34.05°
Altitude:	561.10 km
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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 6 - Input to IRI model

The original hand 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 so that it could be imported into NASCAP2k. The final meshed geometry is shown in Figure 3 and a zoomed in view of the magnetometer boom is shown in Figure 7.

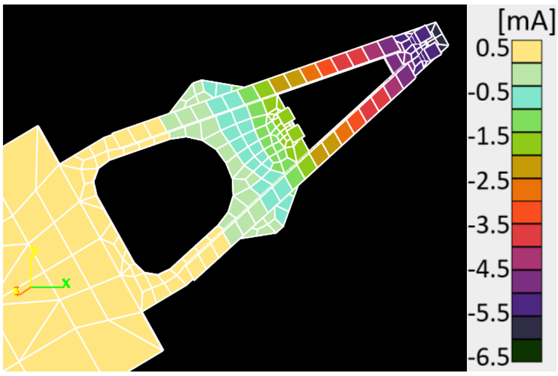

Figure 7 - Surface Charging Current during Earth Flyby, Zoomed to Mag-Boom

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 Figures 4, 5, and 7.

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 tool, ANSYS. The output of this step is surface current density defined over the space of the mag-boom, and is shown in Figure 8.

The surface current density distribution from Matlab is 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 Figure 9. The current paths and 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 36 orientations at 10 degree intervals to get a full 360 degree profile of the induced magnetic field.

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. Recall from Figure 2 that the magnitude of the field observed during flyby was 10nT. The simulation agrees with the observation to a factor of

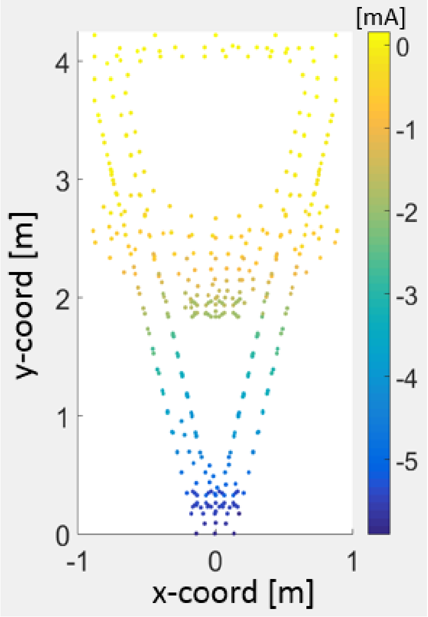

Figure 8 - Matlab Output of Surface Charging Current Density Profile on Mag-Boom, Earth Case

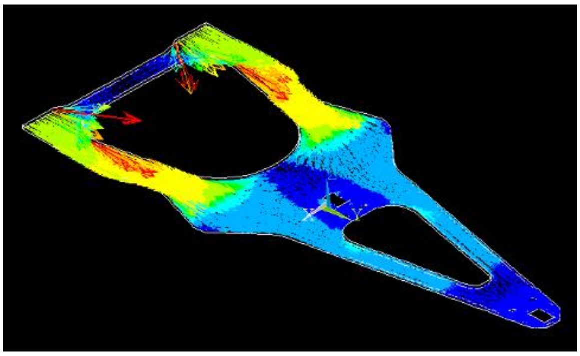

Figure 9 - ANSYS Output; Current Paths and Resulting Magnetic Fields Solved for in the Mab-Boom Structure and Surrounding Space

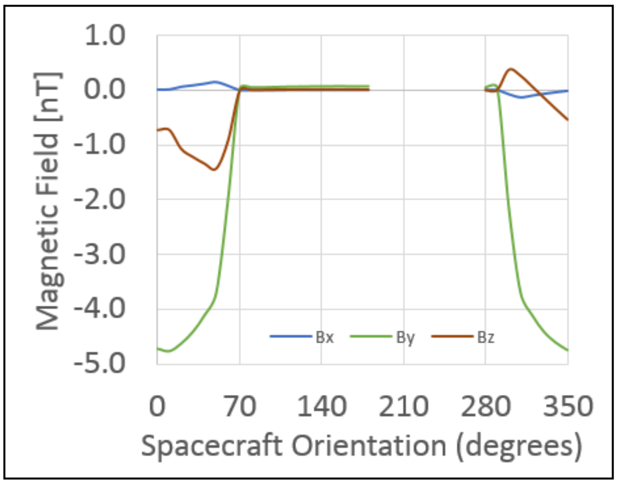

Figure 10 - ANSYS Output of Magnetic Field Components at Inboard Magnetometer. Magnitude is 5nT

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 simplification of the geometry (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.

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 m^{-3} from Voyager data presented in [2]. This is a less dense plasma than at Earth flyby, but it will be 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 JIRE2 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. There are a couple other factors that are different: the spacecraft is in sunlight 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 1.

Table 1 - Some 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	16

The surface charging current at Jupiter was then 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.

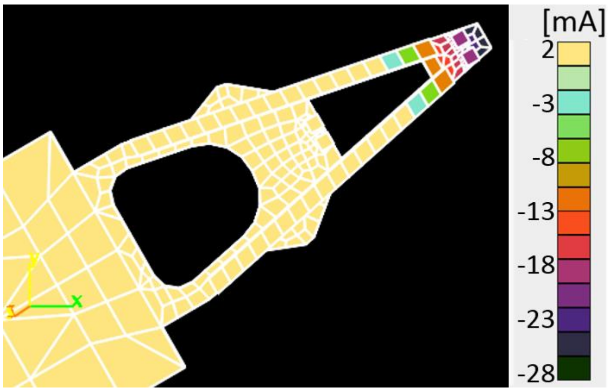

Figure 11 - Surface Charging Current Density at Jupiter

Running the Jupiter surface charging current distribution through ANSYS, we calculate a peak in noise of 16nT, or about 3 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 actually improves at Jupiter.

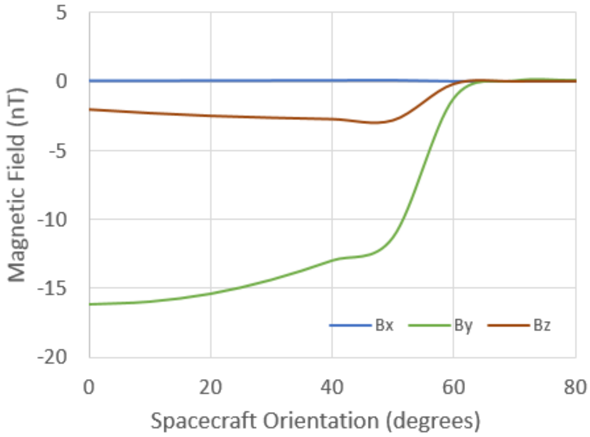

Figure 12 - Induced Magnetic Field at Jupiter. Magnitude is 16 nT

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, and it is easily identifiable because of the non-uniform periodic profile of the noise. The suspected undisturbed magnetic field measurement is highlighted in red in Figure 14.

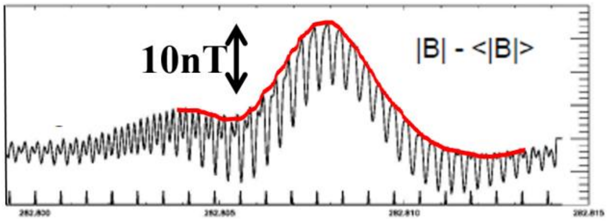

Figure 13 - Magnetometer Data. Undisturbed Data Profile Indicated with Red Line

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 vxB 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 and NASCAP2k 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 easily identify it in the data. Magnetometer science is not at any significant risk from this effect.

7. 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.