Low-Cost Magnetometer Calibration and Distributed Simultaneous Multipoint Ionospheric Measurements from a Sounding Rocket Platform

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Abstract

Low cost and low size-weight-and-power magnetometers can provide greater accessibility for distributed simultaneous measurements in the ionosphere, either onboard sounding rockets or on CubeSats. The Space and Atmospheric Instrumentation Laboratory at Embry-Riddle Aeronautical University launched a midlatitude sounding rocket named SpEED Demon from Wallops Flight Facility in August 2022. SpEED Demon had a comprehensive suite of instruments for electrodynamics and neutral dynamics measurements. Among this suite was one high performance Billingsley magnetometer (TFM65VQS) and six commercial-off-the-shelf magnetometers manufactured by the PNI Corporation (RM3100). Of the six, two PNI magnetometers were situated on a deployable boom on the main payload that also carries the Billingsley magnetometer. The remaining four PNI magnetometers were distributed among four ejectable subpayloads. These low-cost and low SWaP magnetometers can achieve a resolution of approximately 1.5 nT and a precision of +/- 4 nT (one sigma) at 15 Hz in a uniform magnetic field. This performance is sufficient for detecting and measuring field aligned currents as well as a variety of other geomagnetic disturbances. The magnetometers are calibrated against an independently calibrated flux-gate magnetometer inside a Helmholtz cage. Zero field offsets are quantified inside a triple-layer mu-metal zero gauss chamber. This work will present the calibration process, the calibration results, and the flight performance of these sensors from the SpEED Demon sounding rocket launch.

Magnetometers

Main Payload

Billingsley Triaxial Fluxgate TFM65VQS[4]

- Aft axially mounted
- Accuracy: ± 0.75% of full scale (± 100 μT)
- Linearity: ± 0.015% of full scale
- Sensitivity: 100 μV/nT
- 5kHz measurement frequency

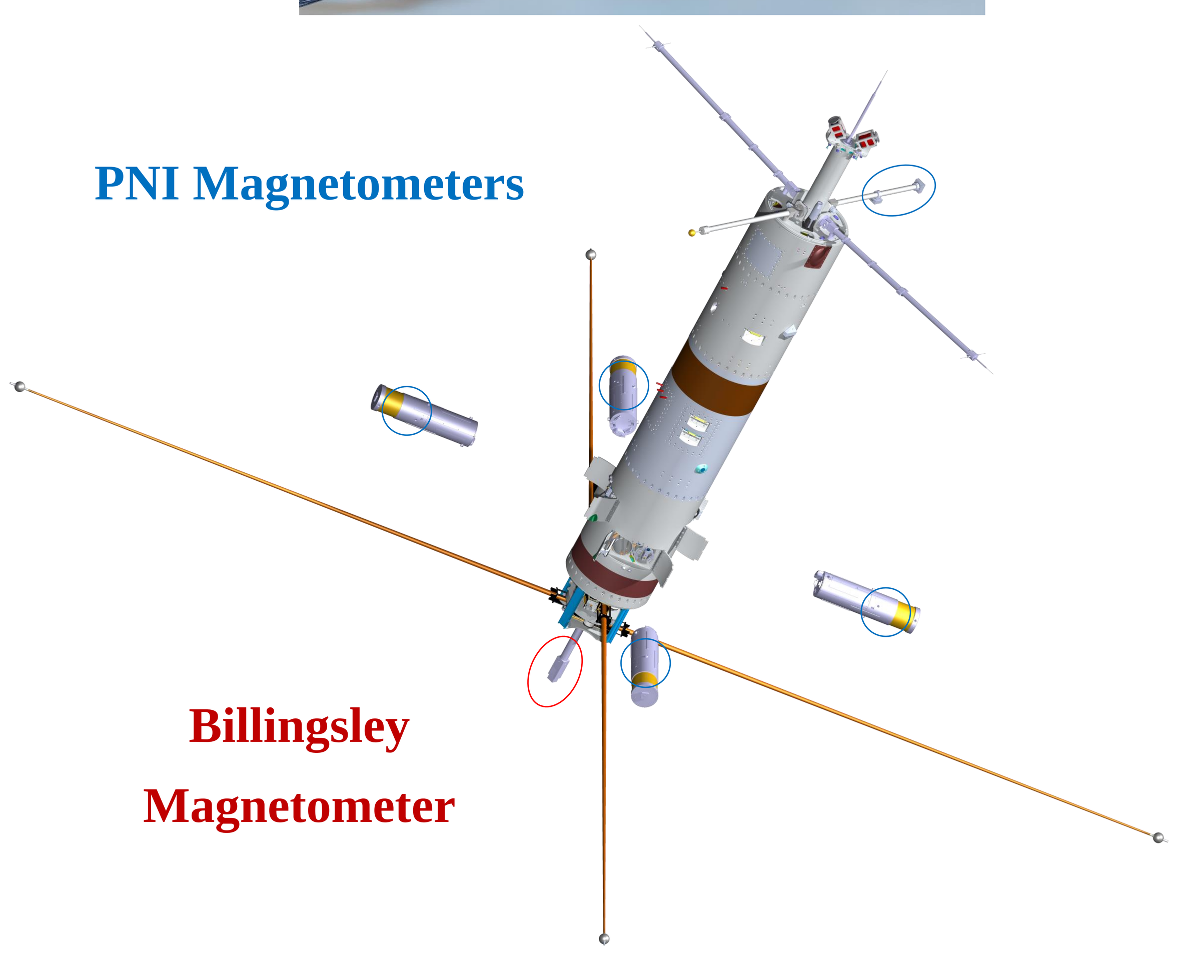
PNI-RM3100[5] x 2

- Located on a fore deployable boom
- 1.5 nT 3-axis sensitivity with proprietary settings
- 15 Hz measurement frequency

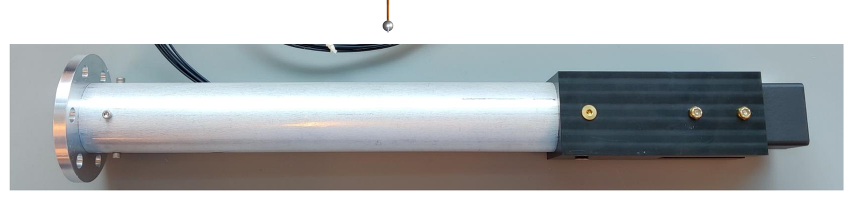
Swarm Subpayload x4

- ~3 m/s deployment speeds relative to main payload
- Deploy parallel to ground, 90° from each other
- GPS positioning
- **PNI-RM3100 Magnetometer[5]**

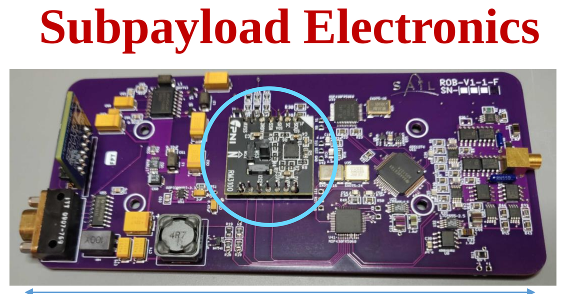
PNI Magnetometers



Billingsley Magnetometer



Subpayload Electronics



14.5 cm length , 6.5 cm width

Subpayload Shell

33.5 cm length, 8.8 cm diameter

Magnetometer Calibration

Helmholtz cage ~1m radius

Coils driven by a Keithley 2200 DC power supply, current sensed by Keithley DMM6500, resulting in:

- Current resolution 0.1 mA
- Magnetic field resolution ~3 nT

MuMetal Zero Gauss Chamber[2] (ZGC) with 1000x attenuation of low-frequency magnetic field inside a zeroed-out Helmholtz cage for zero-field offsets of the magnetometers.

Helmholtz cage is calibrated against an independently calibrated (NIST traceable) FVM-400 MEDA fluxgate magnetometer[3].

Calibration steps:

1. With MEDA magnetometer, measure the currents necessary to cancel Earth's magnetic field inside the Helmholtz cage.
2. Measure the current-to-magnetic-field relationship of the Helmholtz cage.

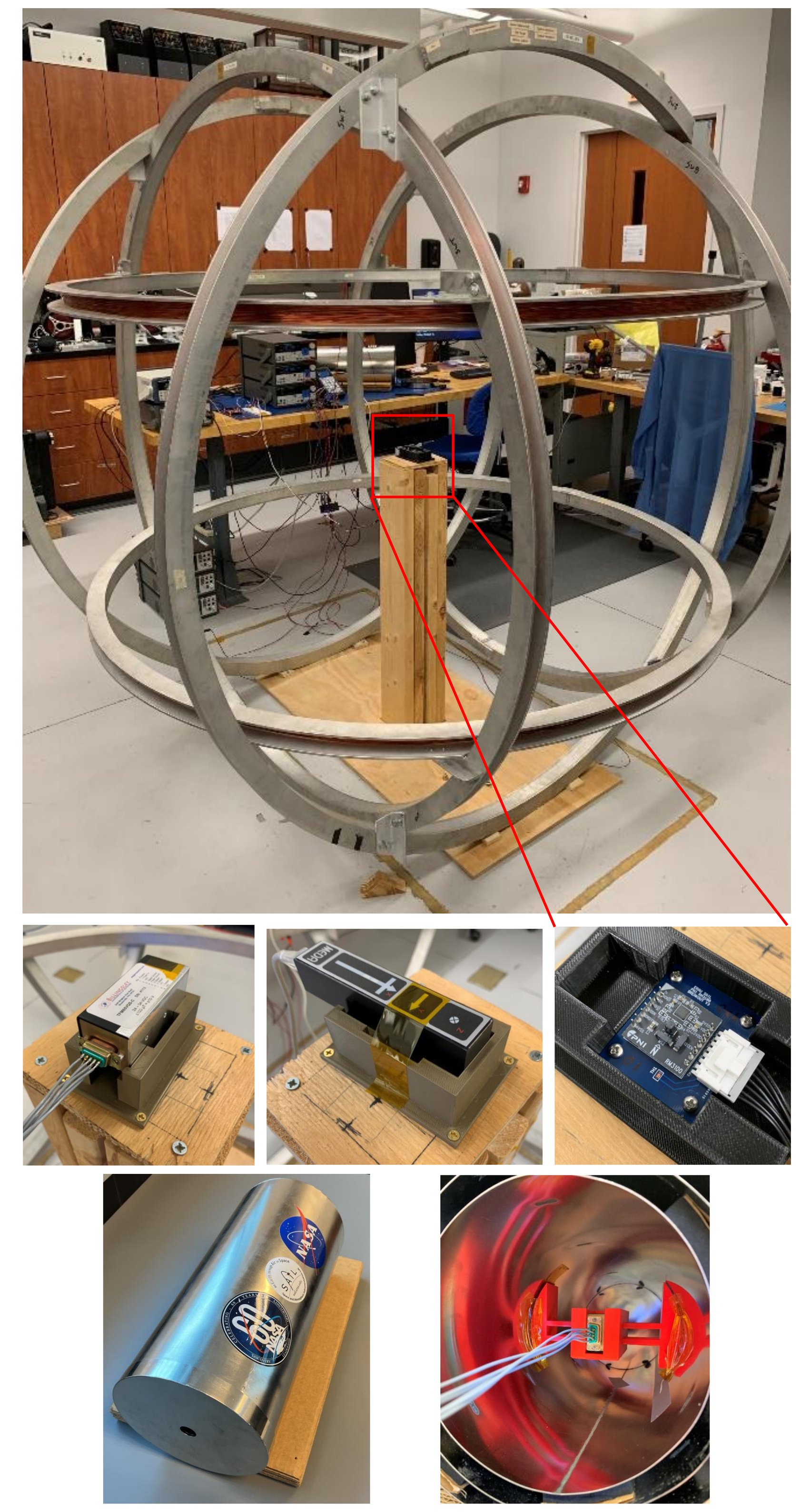
$$\begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} = \begin{bmatrix} A_{xX} & A_{xY} & A_{xZ} \\ A_{yX} & A_{yY} & A_{yZ} \\ A_{zX} & A_{zY} & A_{zZ} \end{bmatrix} \begin{bmatrix} I_X \\ I_Y \\ I_Z \end{bmatrix}$$

1. Measure zero-field offsets by placing magnetometer in ZGC, inside Helmholtz cage
2. Apply magnetic field sweeps on the device under calibration
   Magnetic field is sourced from -35 (-50) to +35 (+50) μT on each axis for PNI (Billingsley).
3. Determine the gain matrix from the collected data.

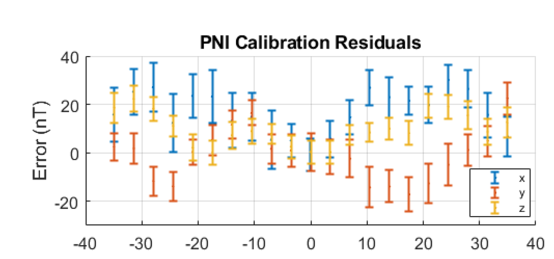
$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} G_{xX} & G_{xY} & G_{xZ} \\ G_{yX} & G_{yY} & G_{yZ} \\ G_{zX} & G_{zY} & G_{zZ} \end{bmatrix} \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} + \begin{bmatrix} O_x \\ O_y \\ O_z \end{bmatrix}$$

M is the sensor output and O is the zero-field offset.

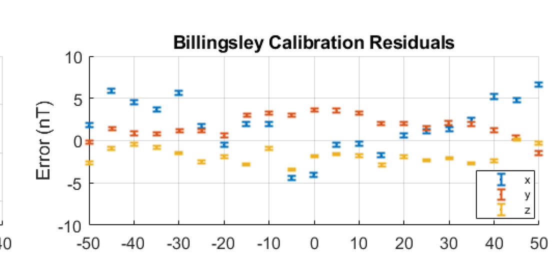
Residuals from the PNI magnetometer calibration show trends indicative of imperfect calibration. Future work will investigate the cause of these trends.



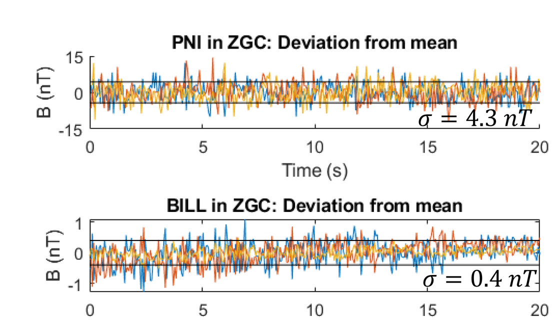
Zero Gauss Chamber: exterior and interior views



* Error bars were taken as the standard deviation (nT) of 100 samples at each calibration step.

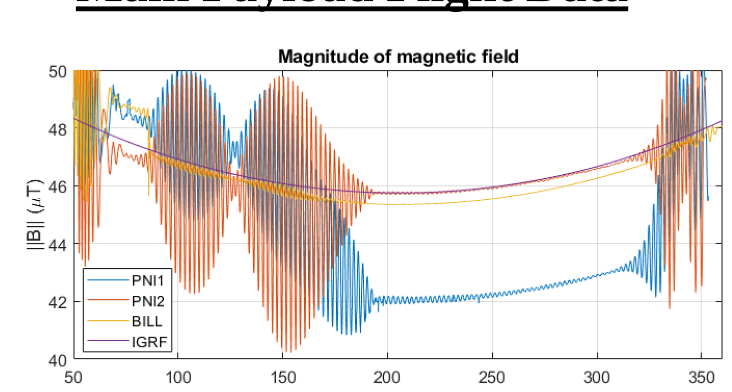


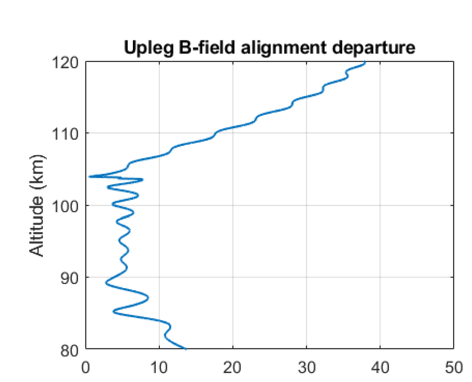
* Error bars were taken as the standard deviation (nT) of 30 seconds of data measured inside the ZGC.

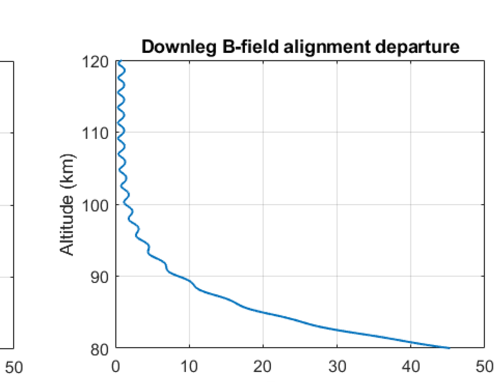


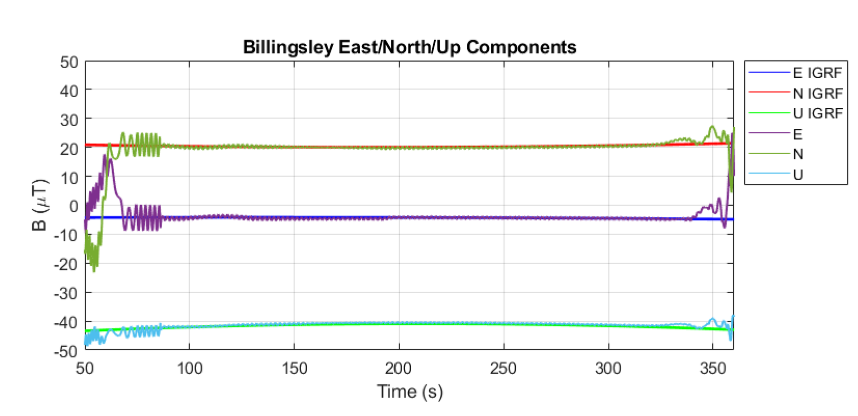
* Magnetometer measurements appear as Gaussian white noise when inside the ZGC.

Main Payload Flight Data

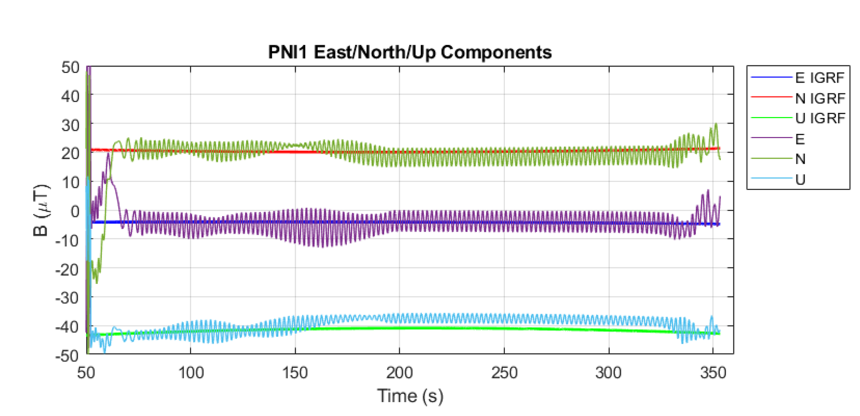


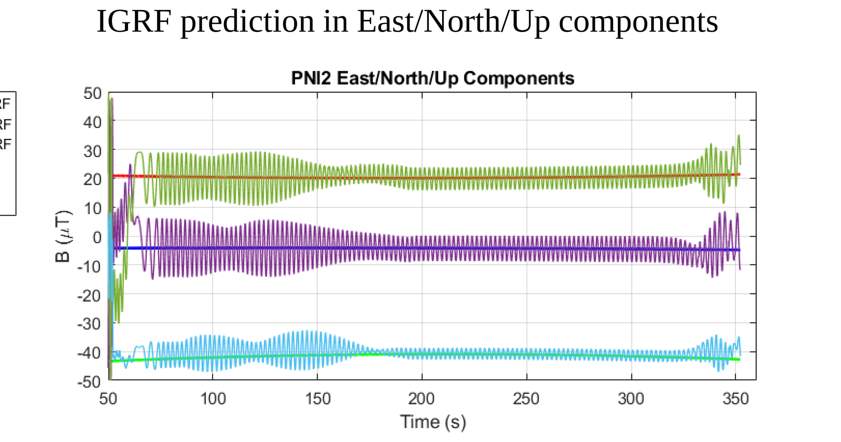






- Mean magnitude difference from IGRF over stable downleg:
  - PNI1: - 3.730 μT
  - PNI2: -0.031 μT
  - Billingsley: -0.403 μT
- Spin effects are visible, indicating an offset magnetic field originating from the rocket
- PNI1 is mounted closer to the main payload than PNI2, suggesting a stronger observed offset
- All three magnetometers show close agreement with IGRF prediction in East/North/Up components

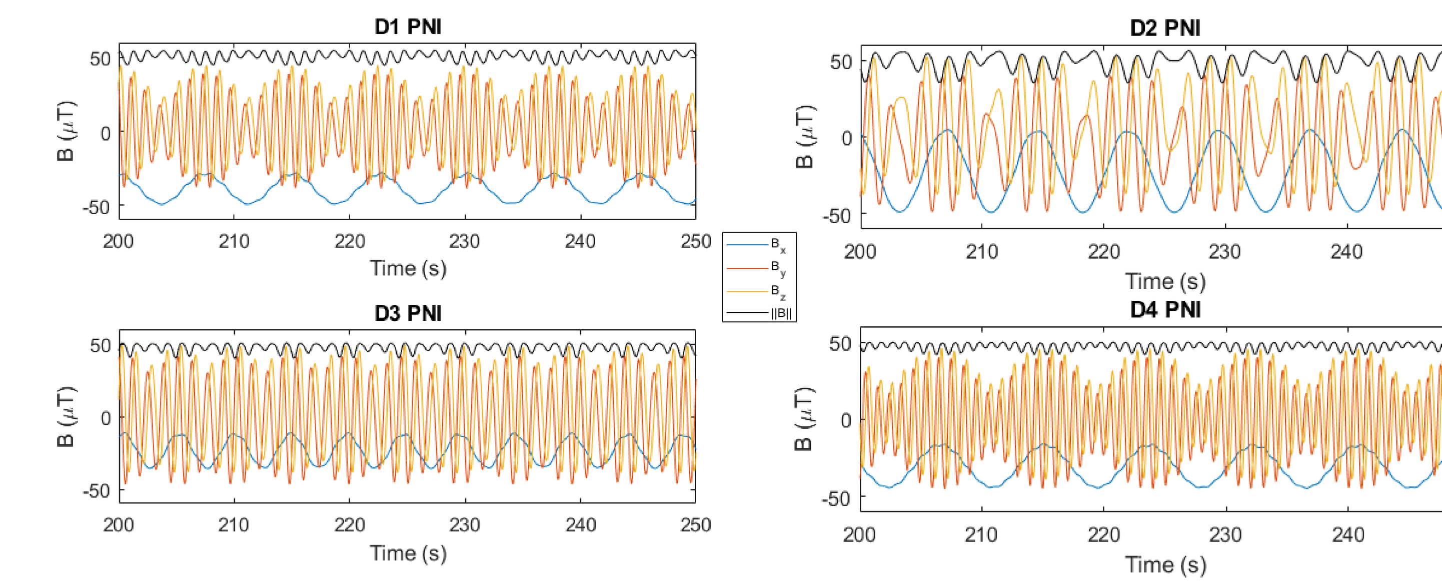




Swarm Attitude Determination

- A single vector in two reference frames is insufficient to determine 3-axis attitude
  - Future work may employ extended Kalman filter to estimate 3-axis attitude with only magnetometer data
- Orientation relative to the local B field is tabulated
  - θ – angle between $\vec{B}$ and subpayload long axis
  - f – frequency of $\theta(t)$
  - ϕ – rotation of $\vec{B}$ around long axis

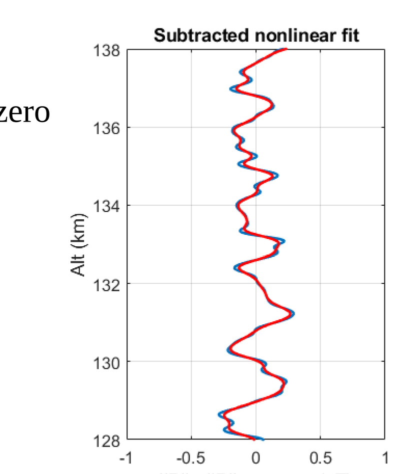
Subpayload	θ_{min} (°)	θ_{max} (°)	$\Delta\theta$ (°)	f (Hz)	$\dot{\phi}$ (Hz)
1	109.6	160.7	51.0	0.113	0.81
2	69.7	161.4	91.8	0.113	0.51
3	96.5	140.8	44.3	0.207	0.78
4	89.4	158.6	69.2	0.118	1.00



Search for Field Aligned Current Signatures

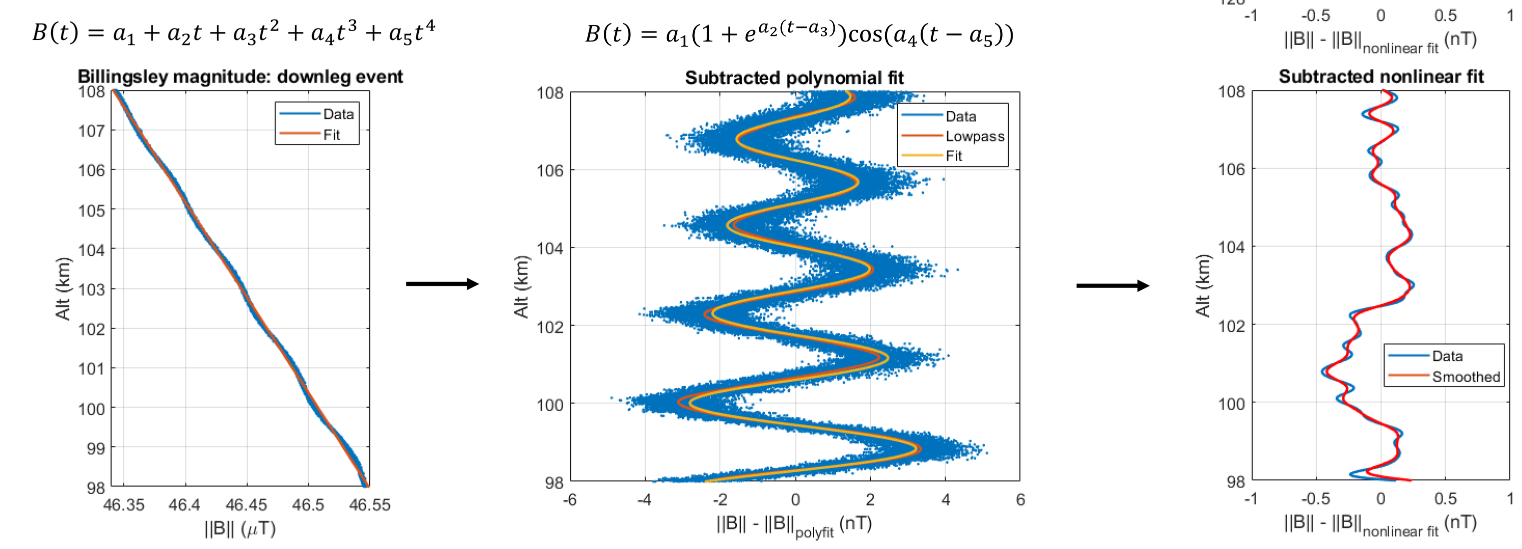
Subtracted a nonlinear fit from two regions of Billingsley flight data

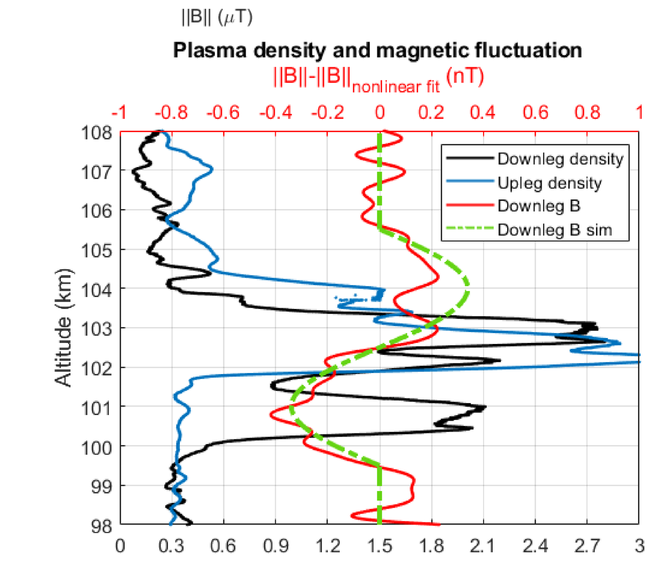
- Downleg 138-128 km: Low plasma density, no FAC expected, centered around zero
- Downleg 108-98 km: Higher plasma density, FAC expected
  - Lower density region shows variation within ± 0.2 nT, centered on zero
  - Higher density region shows > +/- 0.2 nT fluctuation around 102 km
  - Nonlinear fit fails below 98 km due to growth in coning
  - FAC signature: B-field fluctuation is about 0.6 nT peak to peak (± 0.3 nT)



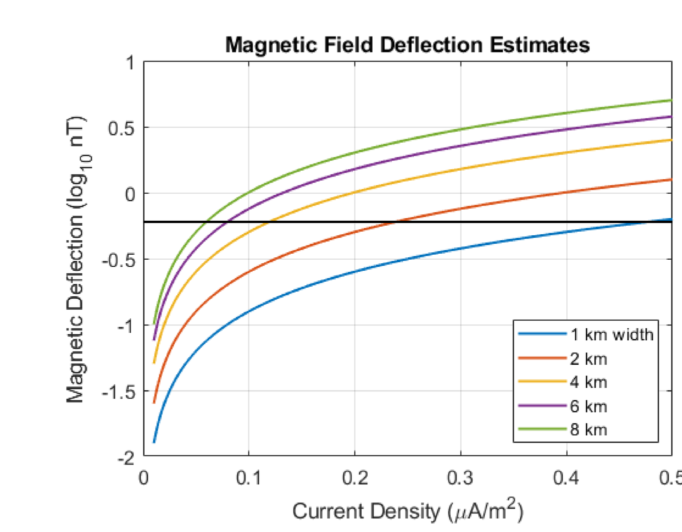
$B(t) = a_1 + a_2 t + a_3 t^2 + a_4 t^3 + a_5 t^4$

$B(t) = a_1(1 + e^{a_2(t-a_3)})\cos(a_4(t - a_5))$





* Simulated magnetic fluctuation: current slab 6 km width, current density ~0.1 $\mu A/m^2$, centered at 102.5 km.



* Infinite current slab approx.: relationship between peak-to-peak magnetic field disturbance and current density. Reference line at 0.6 nT.

Conclusion

- A magnetometer calibration procedure was developed, achieving residuals in the nT scale over Earth's field
- Billingsley and PNI magnetometers measured the background field with close agreement
- Initial estimates of Swarm subpayload motion were derived from magnetometer measurements
- Future work may employ extended Kalman filter to estimate 3-axis attitude with only magnetometer data
- Analysis of Billingsley data revealed magnetic field disturbance with magnitude less than 0.6 nT coincident with plasma density enhancement, possibly consistent with a 6-km current sheet with density ~0.1 $\mu A/m^2$
- These calibrations, swarm attitude estimation, and B field analysis will be used for future sounding rocket missions SEED and Apophis Eclipse Rocket Campaign from White Sands and Wallops.

SCAN ME

References

[1]Space and Atmospheric Instrumentation Lab, http://sail.erau.edu/

[2]Magnetic Shield Corp, https://www.magnetic-shield.com/

[3]Meda, http://www.meda.com/

[4]Billingsley Aerospace & Defense, https://magnetometer.com/

[5]Positioning Navigation Intelligence, https://www.pnicorp.com/