Exploring the Use of Alfvén Waves in Magnetometer Calibration at Geosynchronous Orbit

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Abstract

An Alfvén wave is a type magnetohydrodynamic wave that travels through a conducting fluid under the influence of a magnetic field. Researchers have successfully calculated offset vectors of magnetometers in interplanetary space by optimizing the offset to maximize certain Alfvénic properties of observed waves (Leinweber, Belcher). If suitable Alfvén waves can be found in the magnetosphere at geosynchronous altitude then these techniques could be used to augment the overall calibration plan for magnetometers in this region such as on the GOES spacecraft, possibly increasing the time between regular maneuvers. Calibration maneuvers may be undesirable because they disrupt the activities of other instruments. Various algorithms to calculate an offset using Alfvén waves were considered. A new variation of the Davis-Smith method was developed because it can be mathematically shown that the Davis-Smith method tolerates filtered data, which expands potential applications. The variant developed was designed to find only the offset in the plane normal to the direction of Earth’s magnetic field rarely changes, and theory suggests the Alfvénic disturbances occur transverse to the main field. Other variations of the Davis-Smith method encounter problems with data containing waves that propagate in mostly the same direction. A searching algorithm was then designed to look for periodic high frequency with potential Alfvén waves in GOES 15 data based on parameters requiring that disturbances be normal to the main field and not change field magnitude. Final waves for calculation were hand-selected. These waves produced credible two-dimensional offset vectors when input to the Davis-Smith method. Multiple two-dimensional solutions in different planes can be combined to get a measurement of the complete offset. The resulting three-dimensional offset did not show sufficient precision over several years to be used as a primary calibration method, but reflected changes in the offset fairly well, suggesting that the method could be helpful in monitoring trends of the offset vector when maneuvers cannot be used.

Background on Alfvén Waves

Alfvén waves are an interaction between a charged plasma and a constant magnetic field. Hannes Alfvén first described his nameake waves in 1942 by deriving the wave equation from Maxwell’s equations and the equations of fluid dynamics. A magnetic field causes the charged plasma to move in one direction simultaneously, which constitutes a current. The current in the plasma generates a magnetic field that distorts the total magnetic field, which now constitutes the external field plus the locally generated field. The magnetic pressure of the external field is a restoring force, straightening the field lines and therefore inducing a current in the plasma in the opposite direction of the original current. This new current generates another magnetic field which is again corrected by the magnetic pressure, generating a current in the original direction. Thus, a self-propagating magnetohydrodynamic wave is created. Below is a diagram of an Alfvén wave in a two-dimensional plasma sheet.

There are many kinds of Alfvén waves. In the interplanetary solar wind, the direction of the observed magnetic field is chaotic, while the magnitude is comparatively constant (Leinweber). If Alfvén waves that are nearly circularly polarized, such that total observed field magnitude is conserved, exist at geosynchronous altitude, then the premises required for Leinweber’s application of the Davis-Smith are met and the method could be used to find magnetometer offsets. Circularly polarized, or torsional, Alfvén waves are characterized by the induced component of the observed magnetic field being orthogonal to the main field, and this component of the field affects the direction of the main field. Thus the magnetic field lines in the solar wind move circularly around the vector of the field’s overall direction when under the influence of a torsional Alfvén wave. These waves have the property that the magnetic field changes substantially in the same direction, only its direction. Below is a diagram showing a section of a magnetic field line in the solar wind with a torsional wave propagating along it.

Finding Alfvén Waves

A Fourier transform with a periodic Hamming window was used to help identify the range of frequencies where the two components normal to the main field vary and the magnitude does not. Waves seem to be primarily in the Pc5 frequency range. If such frequencies cannot be found, the window may be omitted from calculation. It is up to the operator to determine the quality of waves. There are cases where having more windows may be better than having too many numbers of windows, or vice versa. Filtering data at the frequencies of the suspected Alfvén waves was investigated, but proved unhelpful. Window lengths are short compared to the period of most of the Alfvén waves. Therefore, an FIR filter could be used to further reduce the effect of noise.

Conclusion

The algorithm alone is not sufficient to independently determine the magnetometer offset in a given orbit. This may be because sufficiently circularly polarized Alfvén waves do not occur often enough at geosynchronous altitude for the method to be successful. The fact that the algorithm predicted artificial offsets fairly well illustrates that the algorithm is most likely sound, but that the input data is not clean enough, as the offset varied significantly more than expected. Varying selection parameters failed to isolate enough sufficiently circularly polarized Alfvén waves, but perhaps better filtering techniques or selection criteria could improve results. In the data, many potential linearly polarized Alfvén waves were observed. Therefore, continuing research will involve attempting to use other algorithms besides Leinweber’s that use linearly polarized Alfvén waves to calculate parts of the offset vector.

References

These graphs show that the algorithm is quite effective at mapping overall trends in the offset. With knowledge of the initial offset, the ability to roughly track changes in the offset vector could be very useful to spacecraft operators.

Finally, the total offset was calculated for GOES 15 for each year from 2011 to 2015. The offset was expected to undergo a random walk of 2 nT/year. Therefore, the standard deviation of each component over the five years should be comparable to 1 nT.

It is not surprising that the offset in the y-direction is the most difficult to determine. The field is often nearly entirely in the y direction, meaning that for each window, much less information is obtained about the offset in the y direction than in the x and z directions. Fewer windows passed selection criteria for other years, which may have contributed to the low precision in the y component. Other components are closer to varying within the expected range. This suggests better precision for the x and z components of the offset.

The effectiveness of the two-dimensional variant of the Davis-Smith Method was tested in three different ways. All windows that passed selection criteria were used for testing, with the belief that noisy windows would average out to zero. Results could potentially be improved by hand-picking offset windows.

First, the overall offset was calculated for the GOES 15 inboard magnetometer in 2011. This alone does not provide very much information. The offset is expected to be credibly small. The returned offset using all windows that passed criteria was (0.7065 -2.3467 3.4037) nT in spacecraft body coordinates. This offset vector has a length of about 4 nT. This is somewhat outside the expected offset range for 2011, but believable.

Next, the response of the algorithm to changes in the offset was testing using artificial offsets. For each component, various offsets in only the component direction were added to the data, the total offset was computed using the two-dimensional Davis-Smith method plus offset combination, and the corresponding component of the returned offset that passed criteria was the known added offset. If the method is accurate, these plots should be linear with a slope of one, indicating that changes in the actual offset are accurately reflected by changes to the returned offset.

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