Unraveling the Multi-Scale Solar Wind Structure Between Lagrange 1-point, Lunar Orbit and Earth's Bow Shock: Better Space Weather Prediction Through Information Theory

Authors: Katherine Holland[1,2], Dr. Katariina Nykyri[1], Dr. Xuanye Ma[1], Dr. Simon Wing[3]

1. Embry-Riddle Aeronautical University, Daytona Beach, FL, 2. NASA Kennedy Space Center, FL, 3. Johns Hopkins University, Baltimore, MD

Abstract

The space weather effects at the Earth's magnetosphere are mostly driven by the solar wind that carries the Interplanetary Magnetic Field (IMF). The incoming solar wind properties at Lagrange point 1 are typically used for developing various space weather forecasts. In this presentation we use several years of data in the solar wind from lunar orbiting ARTEMIS spacecraft and MMS upstream Earth's bow shock to study the multi-scale structure of the IMF as determined by the Wavelet analysis. We determine the lag times between different scales and their dependence on 1) solar wind plasma properties and 2) spacecraft positions. Many solar wind parameters are correlated and anticorrelated with one another. We test the concept of conditional mutual information to isolate the effect of a single parameter and the dependence of various solar wind parameters on the time lags to provide the best/worse correlations between different scales. This will aid in isolating solar wind conditions when single point measurements of the IMF at Lagrange 1 point will likely lead to compromised space weather prediction accuracy.

Background

Information theory is the study of the transfer of information. The goal of communication system is to transmit information, receive it, and decipher it so that the received information is approximately equal to the transmitted information, despite some noise.

Entropy is a measure of uncertainty and is defined by the equation:

$$H = -\sum_i p_i log(p_i)$$

Mutual information allows us to determine what information can be gained from one random variable by examining another and is defined by the equation:

$$I(X;Y) = -\sum_{x,y} p(x,y) log \frac{p(x,y)}{p(x)p(y)}$$

where p(x) is probability that x will occur.

Cross Correlation Analysis can be useful for determining the linear relationships between space weather drivers and its effects, but it falls apart for non-linear relationships. Analyzing mutual information enables us to see nonlinear effects as well.

Raw magnetic field B data from MMS 1, ARTEMIS 1 and 2 fluxgate magnetometer (FGM) were analyzed. Plasma data from ARTIMES electrostatic analyzer (ESA) were also analyzed. Ion velocity was used to calculate an estimated lag time. Ion density and temperature were also examined.

We selected events where both spacecraft MMS 1 and ARTEMIS 1 or MMS 1 and ARTEMIS 2 where located in the solar wind. MMS B data was thoroughly examined and compared to ARTEMIS B data. Windows when absolute value of MMS B data was less than about 10 nanotesla (nT) and comparable to ARTEMIS data were logged. Events where selected with windows greater than one hour. 63 events were collected as of this presentation.

Data preparation for information theory analysis included interpolation of MMS 1, ARTEMIS 1 and ARTEMIS 2 B data into the same time stamps. Vectors of time shifted MMS 1 Bx data were created. Correlation coefficients and mutual information were calculated for each time shifted vector and plotted against time lag. When correlation coefficient and mutual information main peaks give the same time-lag, the large-scale structure moves from the Moon's orbit to the Earth mostly intact and moves with constant velocity. An estimated time lag was calculated initially by dividing distance between the two spacecraft and the ion velocity from the ARTEMIS spacecraft Electrostatic Analyzer (ESA).

We estimated lag time (to compare against the MI and cross correlation results) also by doing minimum variance analysis of the magnetic field (MVAB) to find the direction along which the magnetic field is changing the least. Surprisingly, the lag time did not often match that from mutual information or cross-correlation, suggesting that A) information travels at different speed and angle with respected to solar wind flow, or B) there is some internal periodicity in the solar wind which can dominate mutual information. To obtain an adjusted lag time, we tested adding and subtracting the magnetosonic wave velocity to the solar wind flow vector:

$$v_f = \left(\frac{1}{2}\left(c_s^2 + v_A^2 + \sqrt{(c_s^2 + v_A^2)^2 - 4c_s^2 v_A^2 cos^2\theta}\right)\right)^{1/2} * \hat{e}$$

where c_s is the speed of sound in the solar wind, v_A is the Alfven speed, θ is the angle between the fast mode wave direction and the magnetic field direction, and $\hat{e}$ is the fast mode wave direction.

The equation for estimated lag time used in this analysis is:

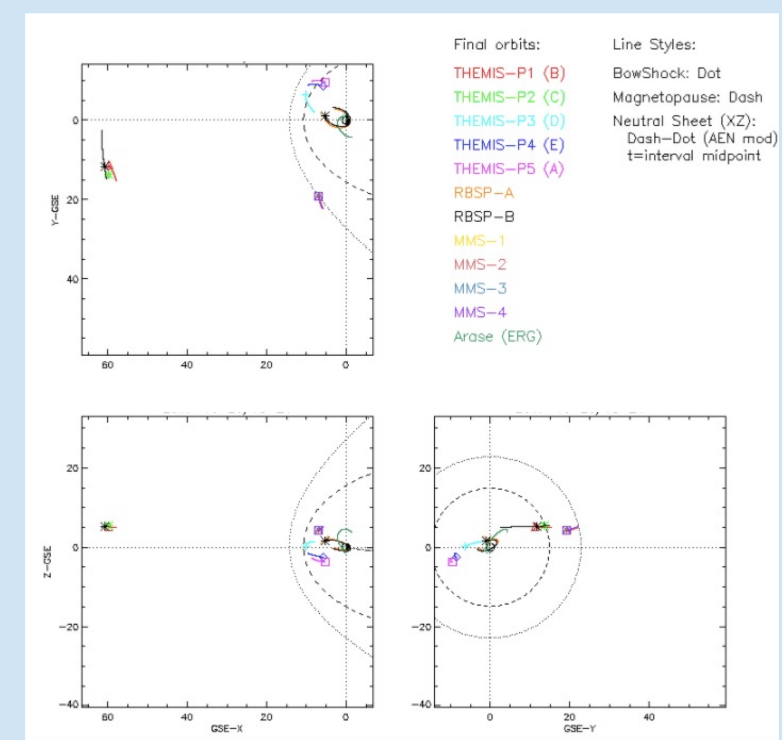
$$t = \frac{\vec{R} \cdot \hat{n}}{(\vec{u} \pm \vec{v_f}) \cdot \hat{n}}$$

where $\hat{n}$ is the direction of minimum variance in magnetic field, $\vec{R}$ is the displacement vector between MMS and ARTEMIS spacecraft, and $\vec{u}$ is the solar wind velocity measured by the ARTEMIS spacecraft.

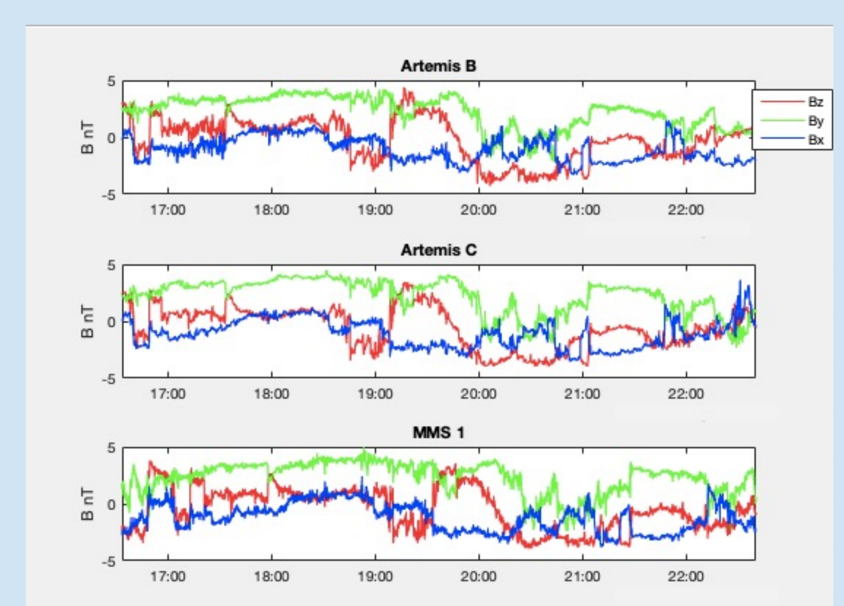
Wavelet Transform analysis was also conducted for the Bx data for each of the three spacecraft.

Results for One Event

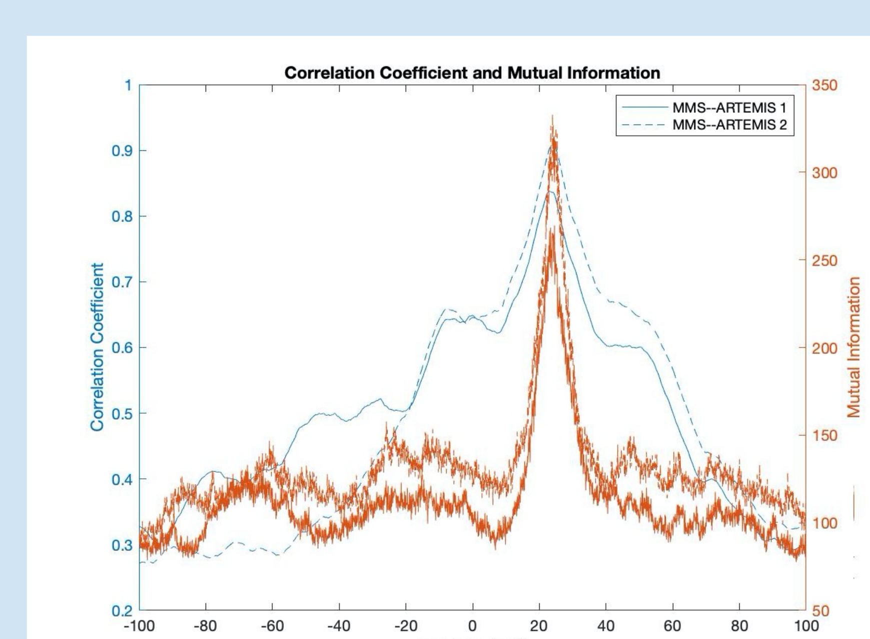
Results for one event are presented here. The plot below shows each of the MMS and THEMIS spacecraft. ARTEMIS 1 and 2 are THEMIS B and C respectively. Note that delta y between the ARTEMIS and MMS spacecraft for this event is about 4 to 7.5 Earth radii. This is a relatively low delta y.



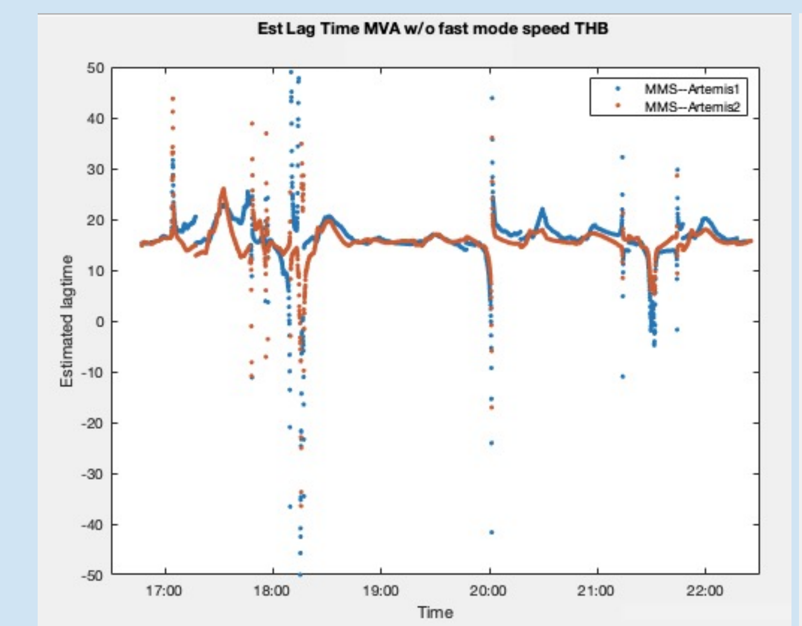
The x, y, and z components of the magnetic field data from the MMS 1, ARTEMIS 1, and ARTEMIS 2 spacecraft are shown below. Note that a trend can be seen by observing this data. Similarities in ARTEMIS 1 and 2 data can be seen. The same similarities can be seen in MMS 1 data if the MMS 1 data is shifted about 24 minutes to the right. This represents magnetic field structures moving from the region around the Moon (where the ARTEMIS spacecraft are located) to the region around the Earth.

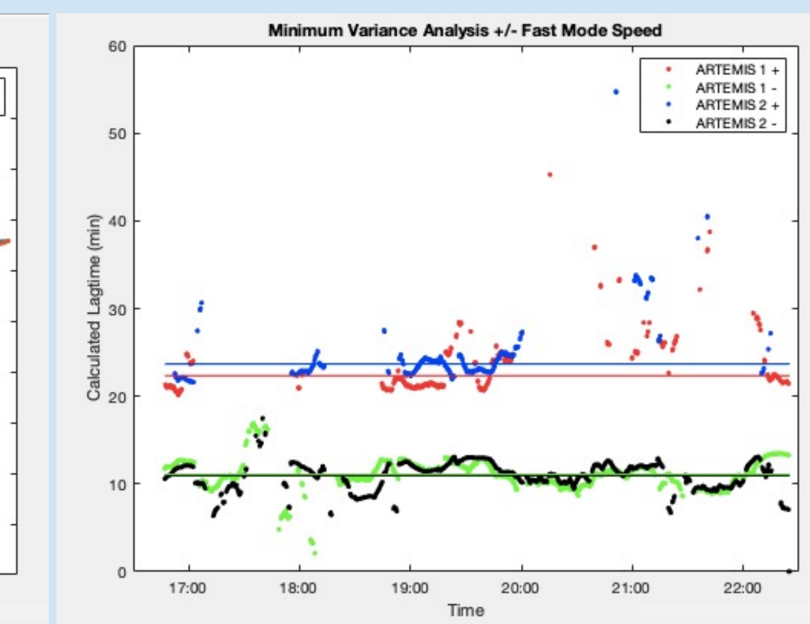


Linear cross correlation coefficients and mutual information plotted against lag times for the same event are shown below. Solid lines represent MMS 1 and ARTEMIS 1 Bx data; dashed lines represent MMS 1 and ARTEMIS 2 Bx data. Both the MI and cross correlation peak at about 24 minutes for this event.

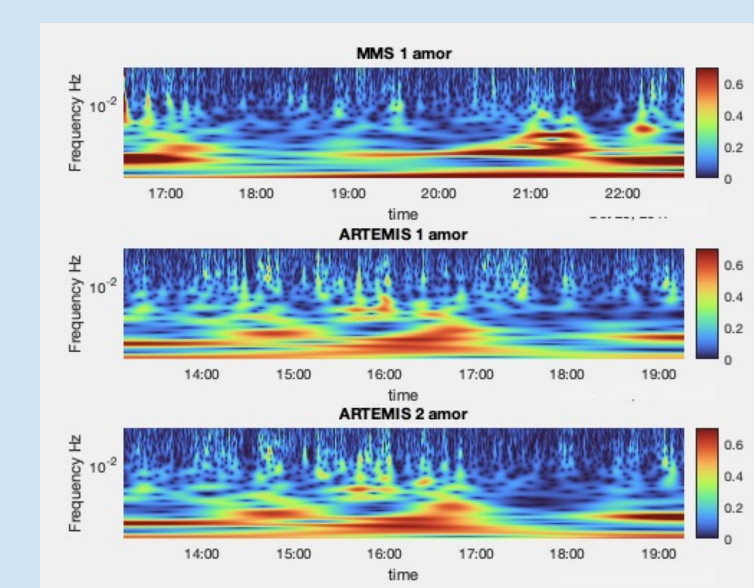


A minimum variance analysis of the magnetic field (MVAB) was performed in order to determine direction of least variance in magnetic field. Fast mode speed of a magnetosonic wave was also calculated and added to and subtracted from the solar wind velocity in order to determine estimated lag times. The results are shown below. For this event, without adding or subtracting the fast mode speed, the estimated lag time was about 15 minutes. Adding the fast mode speed resulted in a lag time of about 23 to 24 minutes and subtracting the fast mode speed resulted in a lag time of 10 to 11 minutes. This suggests that the information velocity from the Moon to Earth is the superposition of the solar wind flow velocity and magnetosonic velocity.

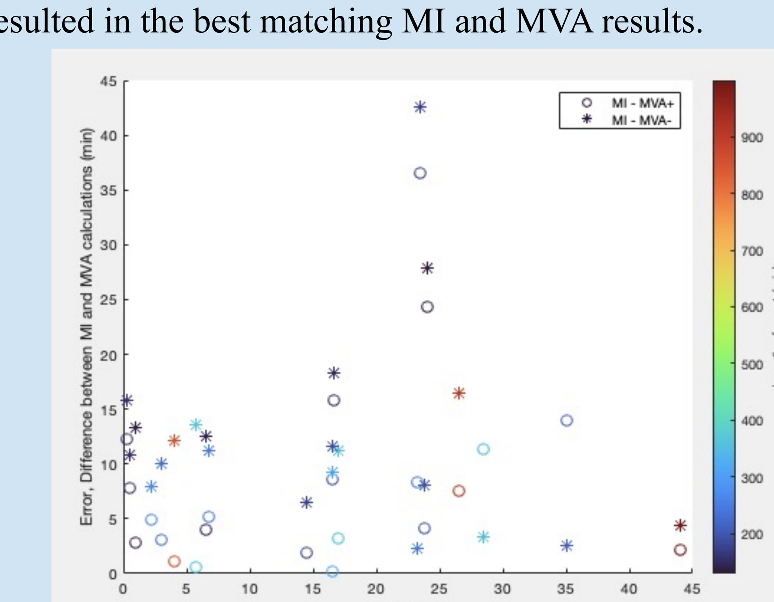




Wavelet transform spectrograms (amor wavelet) of MMS 1 and ARTEMIS 1 and 2 for the same event are shown below.



At the time of this presentation, 22 events have been examined. It was found that the error between the MI and the MVA results depended on the delta y between the MMS and ARTEMIS spacecraft and the length of each event. The plot below shows the differences between the MI and MVA results compared to delta y and length of each event for 22 events. It was found that the longer events and the events with the lowest delta y, resulted in the best matching MI and MVA results.



Conclusion

This preliminary analysis of the solar wind lag times shows that information theory can be very useful in understanding and predicting arrival of space weather events. Cross correlation analysis can be useful for determining the linear relationships between space weather drivers and its effects, but it falls apart with non-linear relationships. Analyzing mutual information enables us to unravel both the linear and non-linear relationships between space weather drivers and their effects.