Testing Shock Jump Predictions: THEMIS Observations

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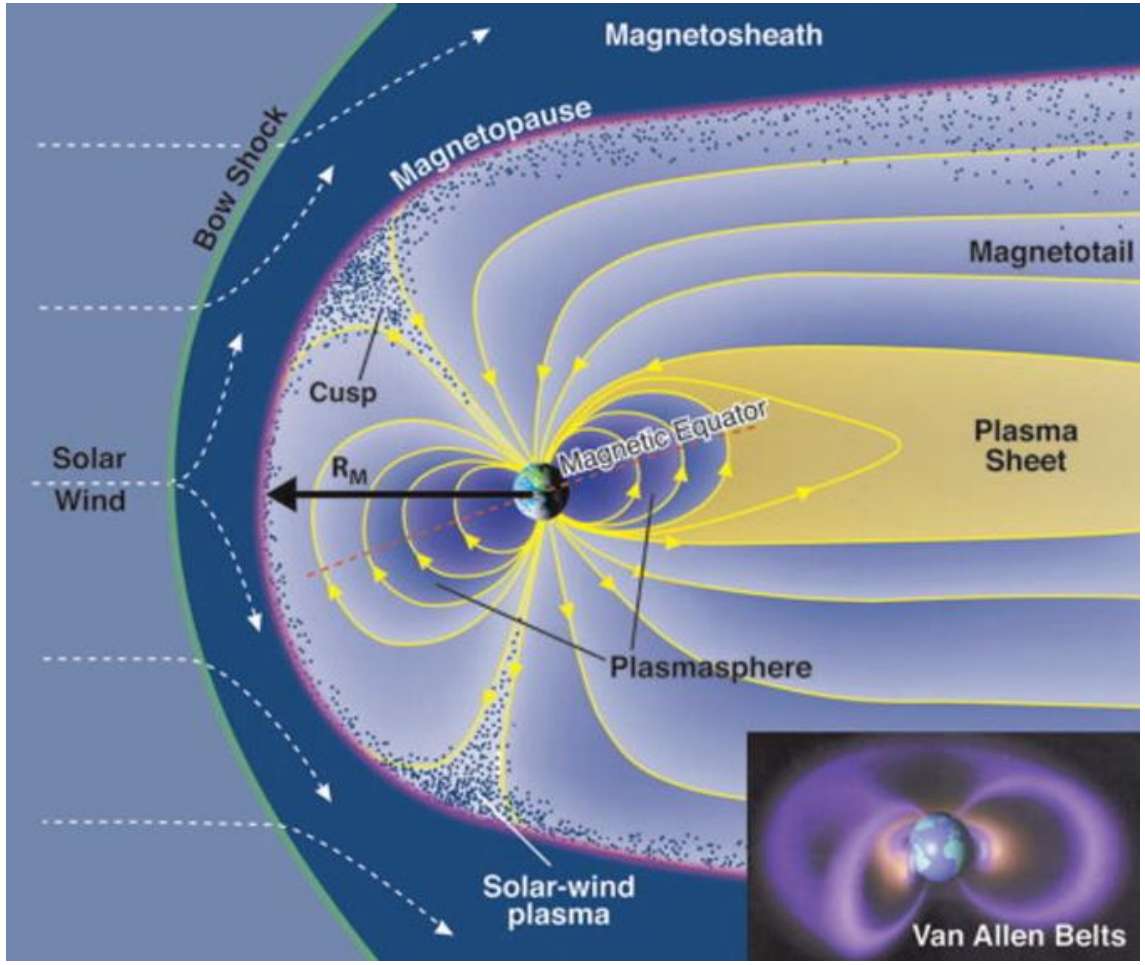
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Motivation and Objective

- Earth's Bow Shock is a natural and easily accessible environment to study collisionless shock physics.
- The textbook framework for describing shock transitions is ideal Magnetohydrodynamics (MHD) and its Rankine-Hugoniot jump conditions. Real world shocks though are turbulent and non stationary which are conditions the ideal MHD ignore.
- **Do the Rankine-Hugoniot jump conditions actually hold in nature and predict the space plasma behavior observed by THEMIS accurately?**
- Answering this shall test the reliability of current models used in space weather forecasts.

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The Solar Wind and Earth

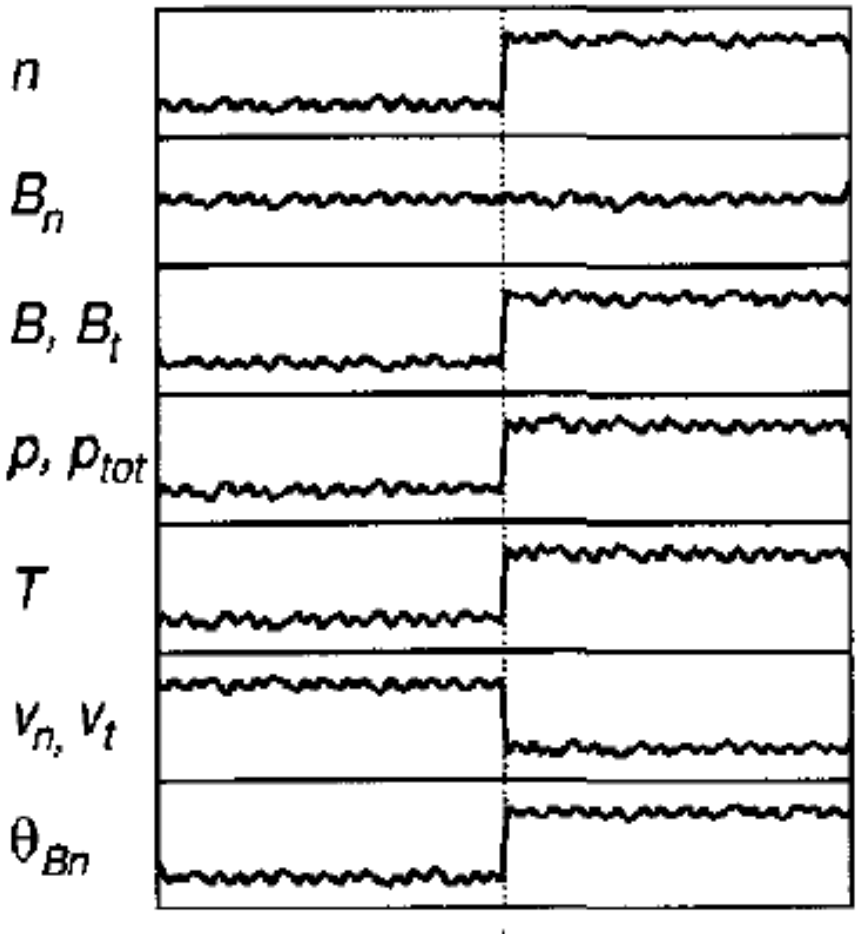


- Shock: Supersonic flow discontinuity.
- Solar Wind: A continuous flow of charged particles from the sun.
- The Obstacle: Earth's magnetic field.
- Bow shock: Boundary where Supersonic deceleration and kinetic to thermal energy conversion occurs.
- Magnetosheath: A turbulent transition region of shocked solar wind plasma.

Credit: Kivelson and Bagenal, (2007)

MHD Jump Conditions

- MHD Theory: Plasma is treated as a continuous magnetized fluid.
- Conservation of Mass, Momentum and Energy.
- Rankine-Hugoniot relations: Prediction of “Jump” parameters.
- Expectations:
  - Density (n) and Magnetic Field (B): sharp increase (Compression).
  - Temperature: Sharp Increase (Heating).
  - Velocity: Sharp decrease (Deceleration).



Credit: Baumjohann and Treumann (1SSc)

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Rankine-Hugoniot Jump Conditions

MHD Mass Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

MHD Momentum equation

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

Faraday's Law and Frozen-In condition

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Gauss's Law of Magnetism

$$\nabla \cdot \mathbf{B} = 0$$

1st condition: Conservation of mass flux

$$\mathbf{n} \cdot [n\mathbf{v}] = 0$$

2nd condition: Conservation of momentum flux

$$\mathbf{n} \cdot [n m_p \mathbf{v}\mathbf{v}] + \mathbf{n}\left[p + \frac{B^2}{2\mu_0}\right] - \frac{1}{\mu_0}\mathbf{n} \cdot [\mathbf{B}\mathbf{B}] = 0$$

3rd condition: continuity of tangential electric field

$$[\mathbf{n} \times \mathbf{v} \times \mathbf{B}] = 0$$

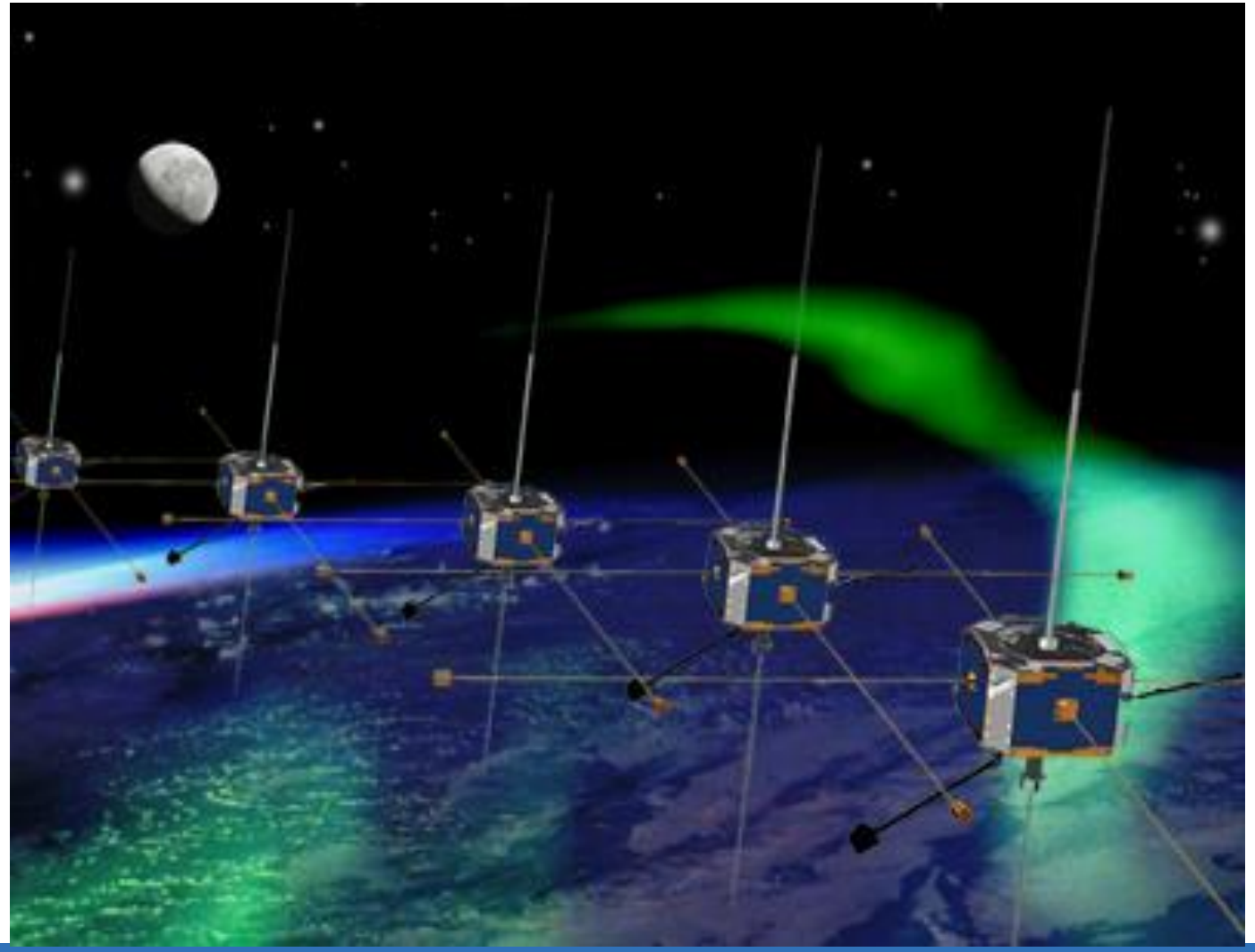
4th condition: Conservation of magnetic flux

$$\mathbf{n} \cdot [\mathbf{B}] = 0$$

Where $[X] = X_d - X_u$ denotes the jump across the shock and **n** is the shock normal vector

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The THEMIS Mission

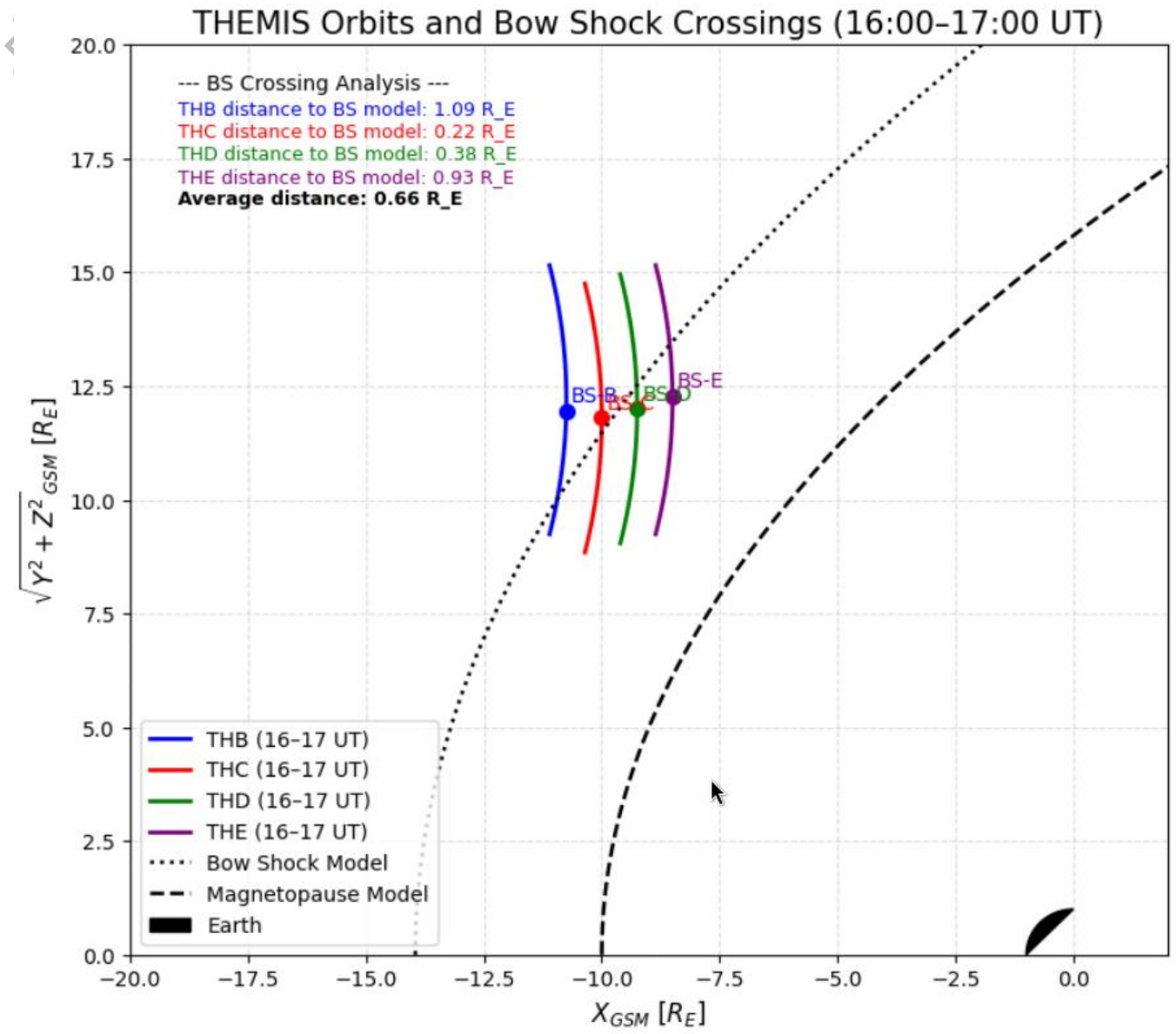


- Mission Overview: Five satellites (A-E) studying magnetospheric energy release.
- Instrumentation used:
  - FGM (Fluxgate Magnetometer): Magnetic Field Vector.
  - ESA (Electrostatic Analyzer): Ion Density, Velocity Vector and Plasma Pressure.

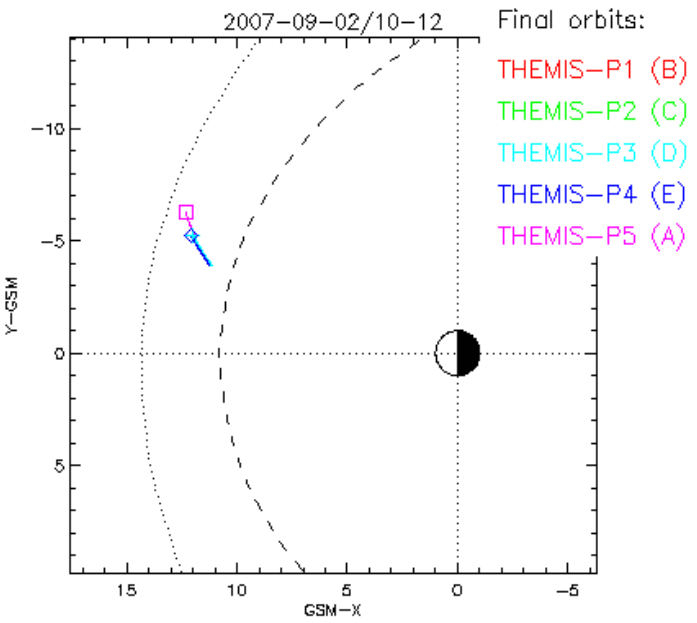
Credit: NASA

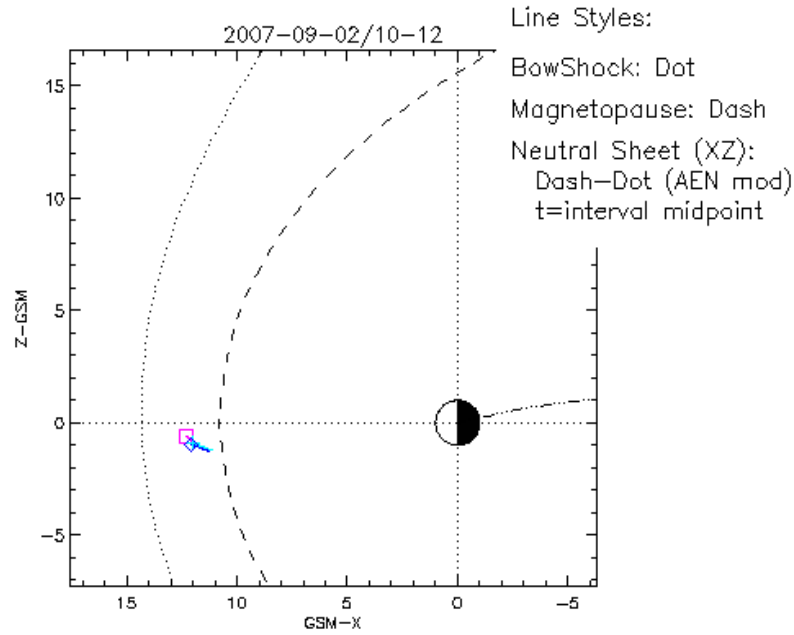
Event Selection

- **Event:** July 26, 2007 (16:20 – 16:40 UT) and September 2, 2007 (11:50 – 12:10 UT)
- High quality FGM and ESA data available during this period.
- NASA's THEMIS spacecraft are in the same orbit.
- This provides a unique opportunity to check RH relations using multi-spacecraft measurements.
- We determine the bow shock normal using a different method.



We processed the 2007 THEMIS measurements

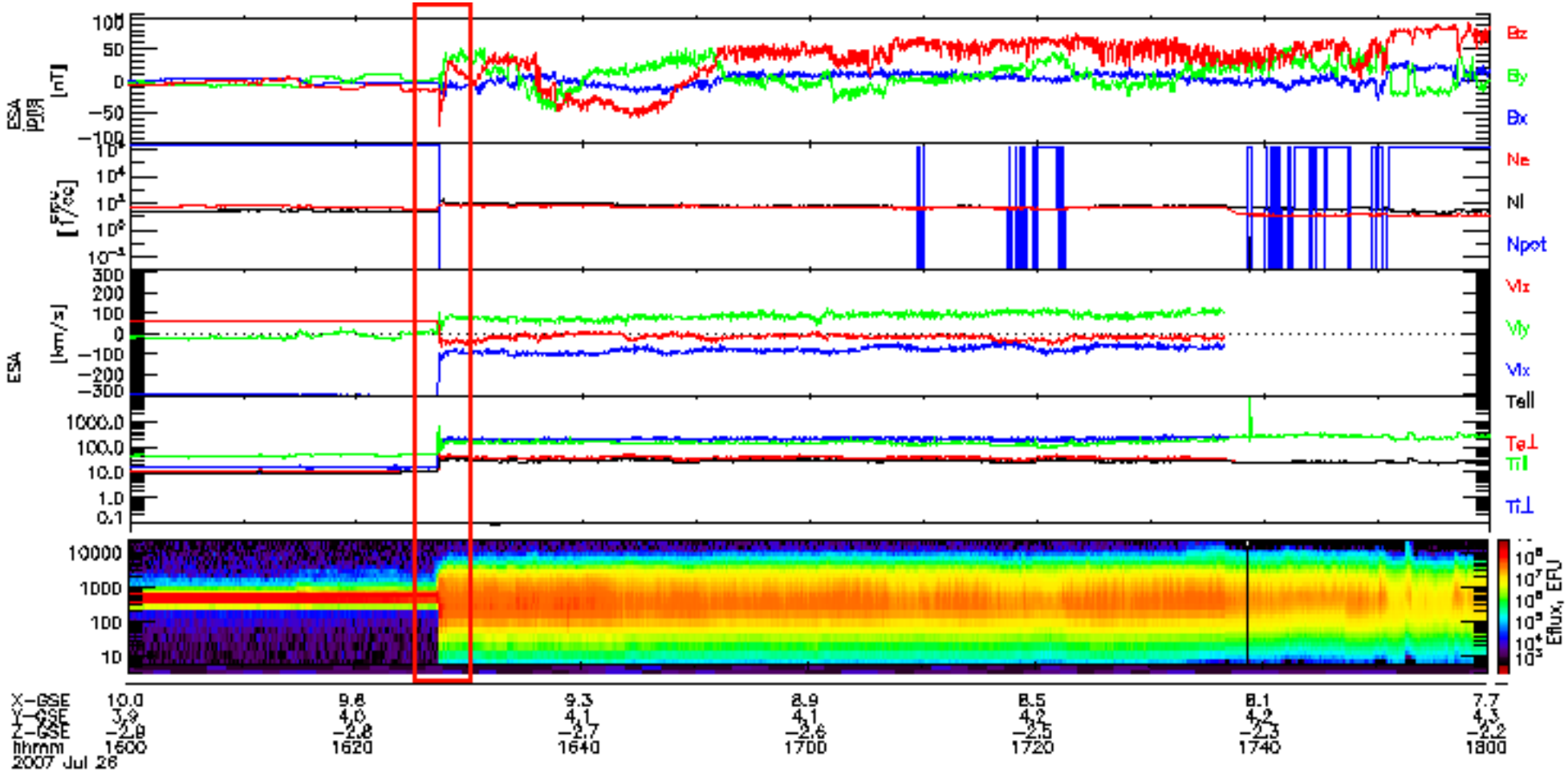




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Event Selection

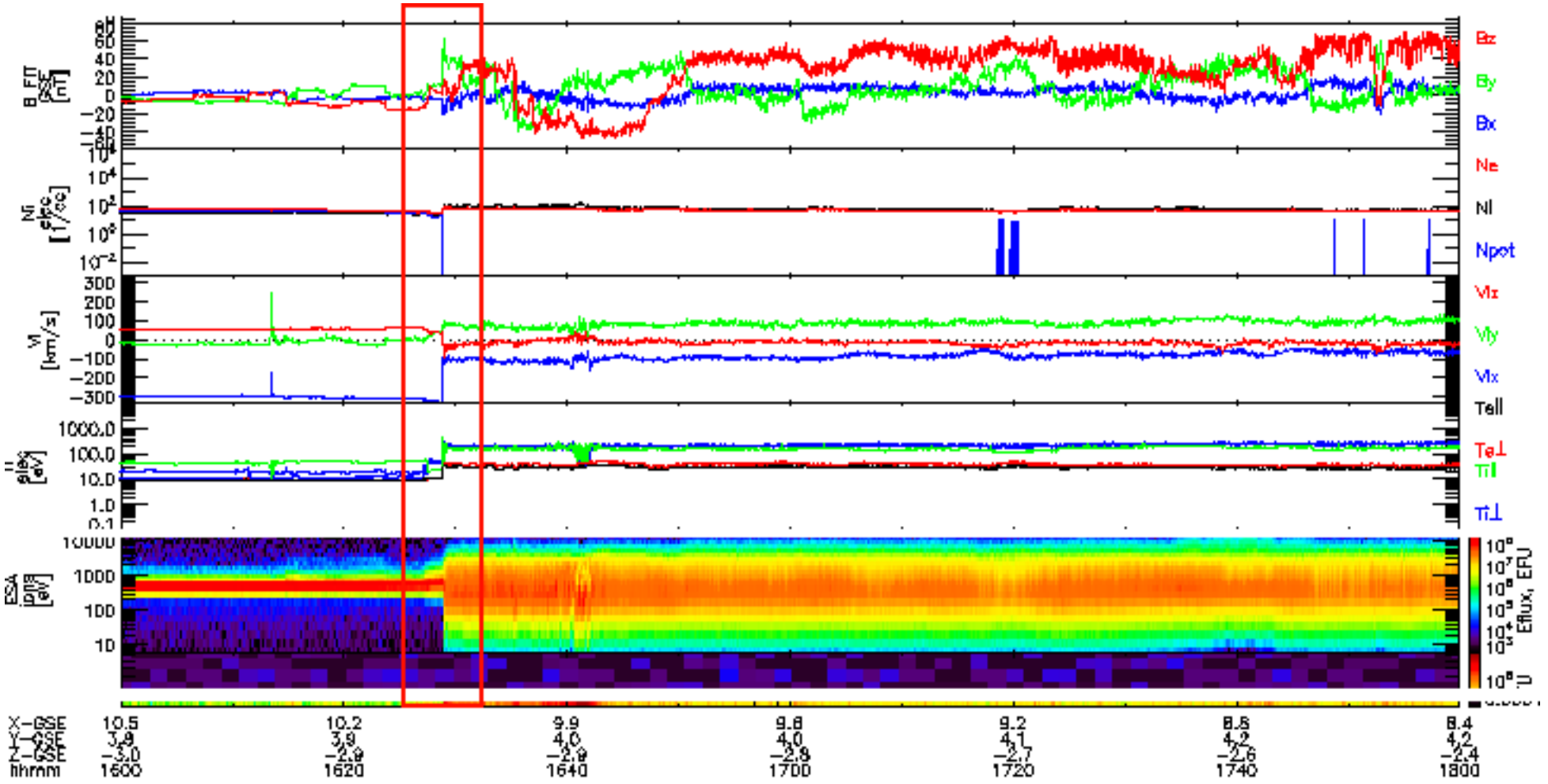
- THEMIS B on July 26, 2007, from 16:20 to 16:40 (UT)



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Event Selection

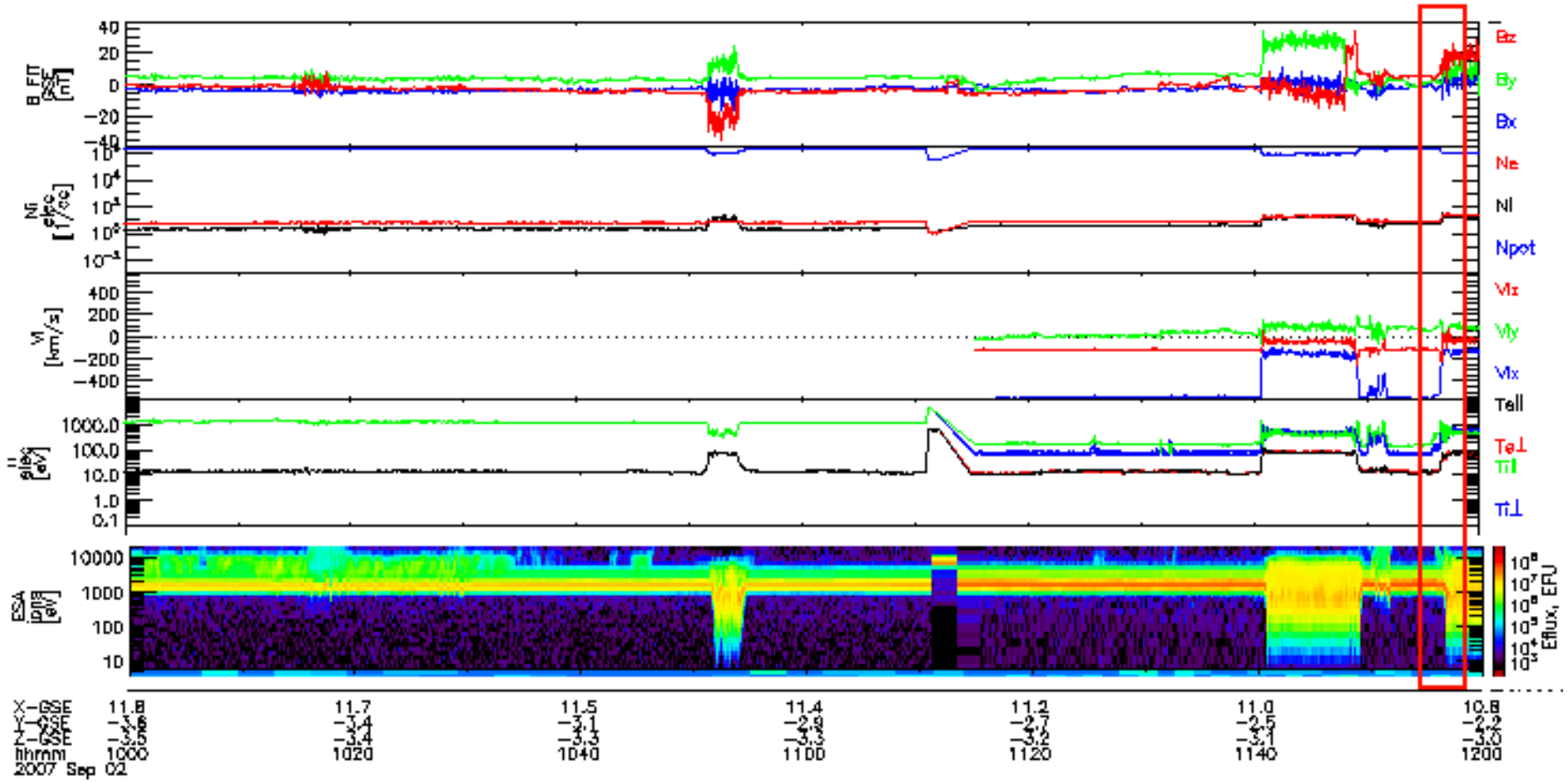
- THEMIS C on July 26, 2007, from 16:20 to 16:40 (UT)



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Event Selection

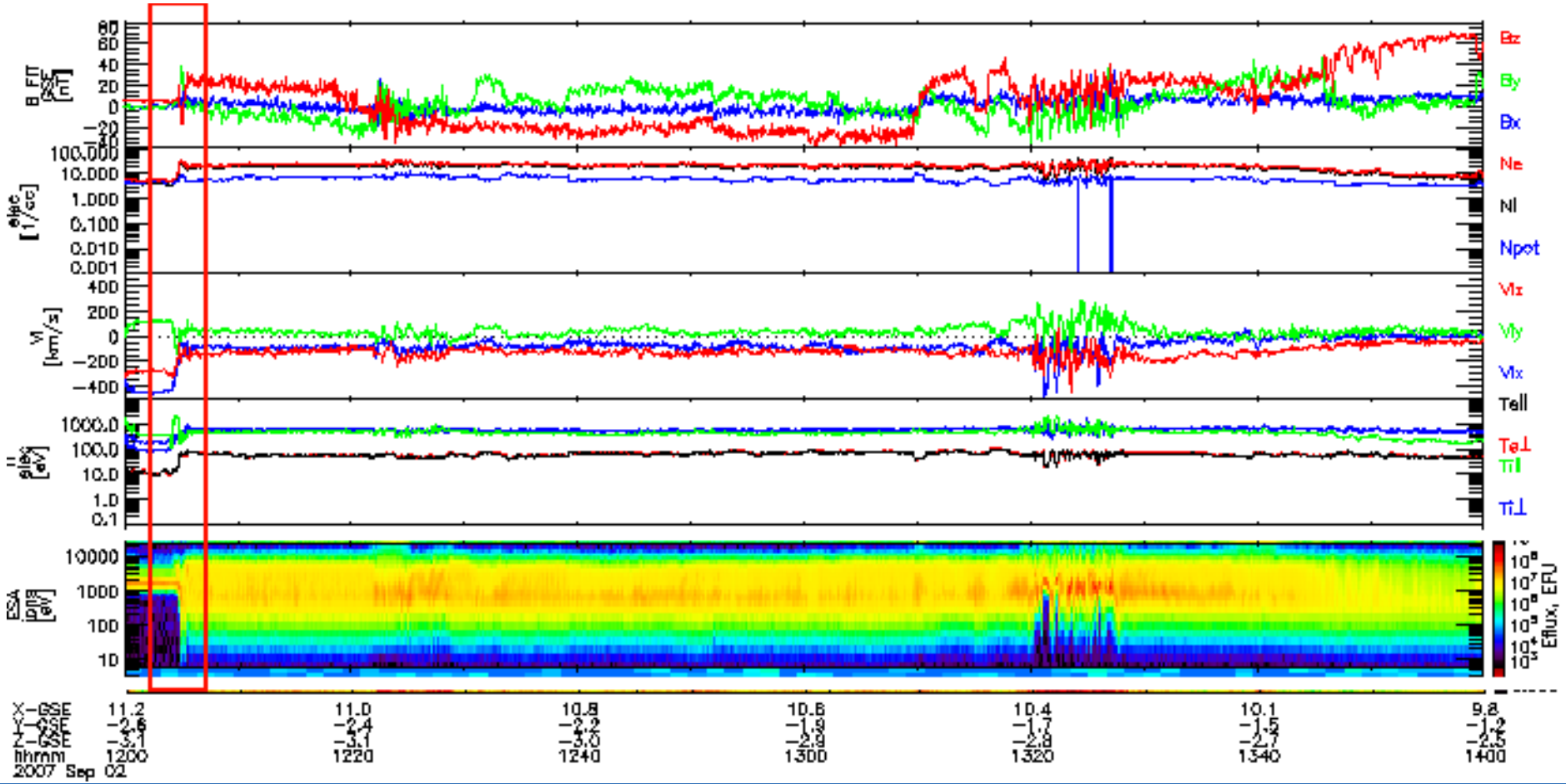
▶ THEMIS B on September 2, 2007, from 11:50 to 12:00 (UT)



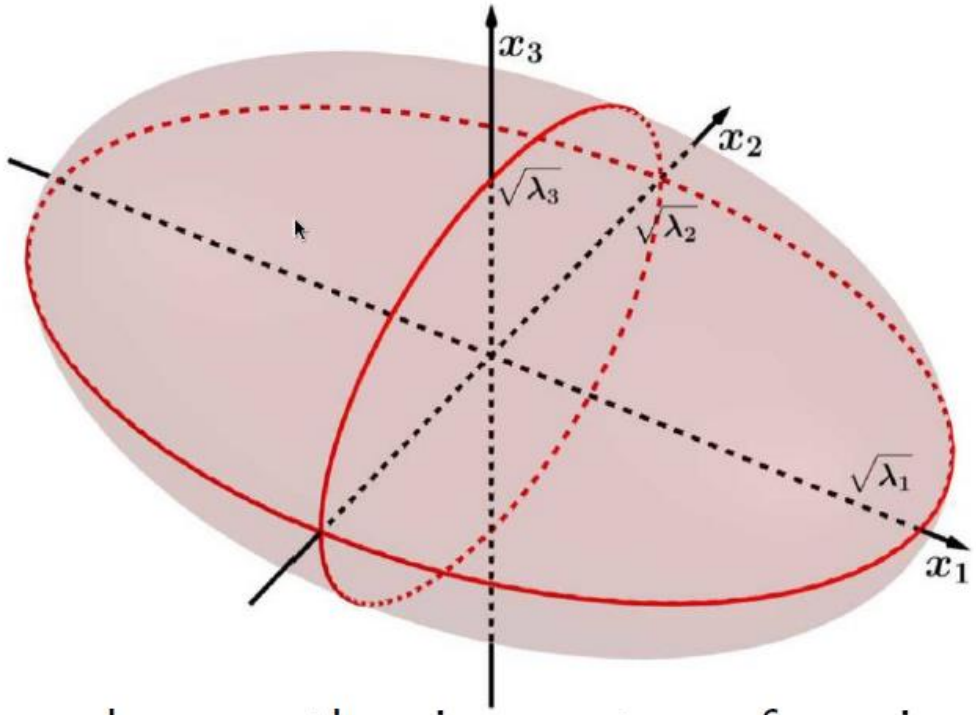
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Event Selection

- THEMIS E on September 2, 2007, from 12:00 to 12:10 (UT)

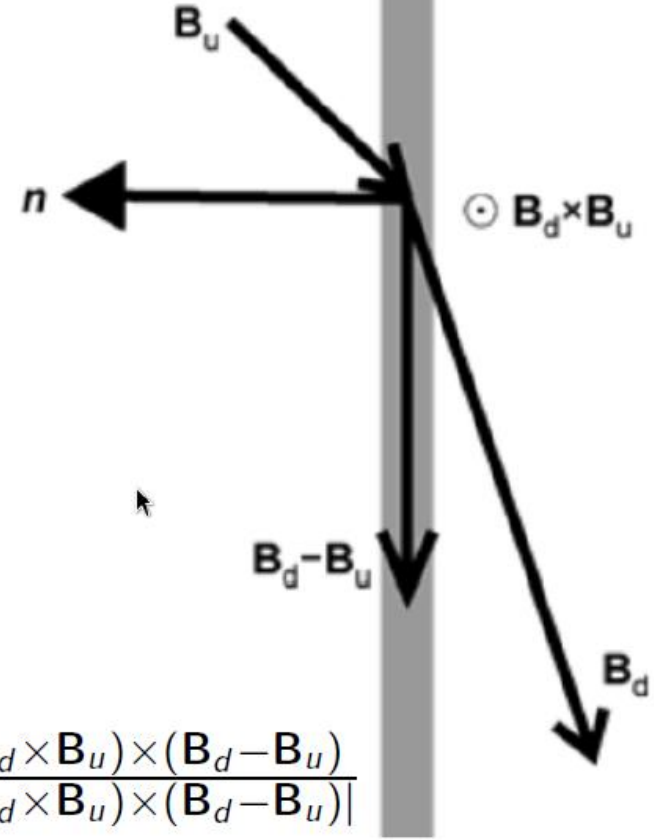


Bow shock normal determination I



$\mathbf{x}_1$, $\mathbf{x}_2$, and $\mathbf{x}_3$ are the eigenvectors of maximum, intermediate, and minimum variance, respectively, with λ_1, λ_2, and λ_3 being the corresponding eigenvalues.

$\mathbf{B}_u$ and $\mathbf{B}_d$ are the upstream and downstream magnetic field vectors, respectively.



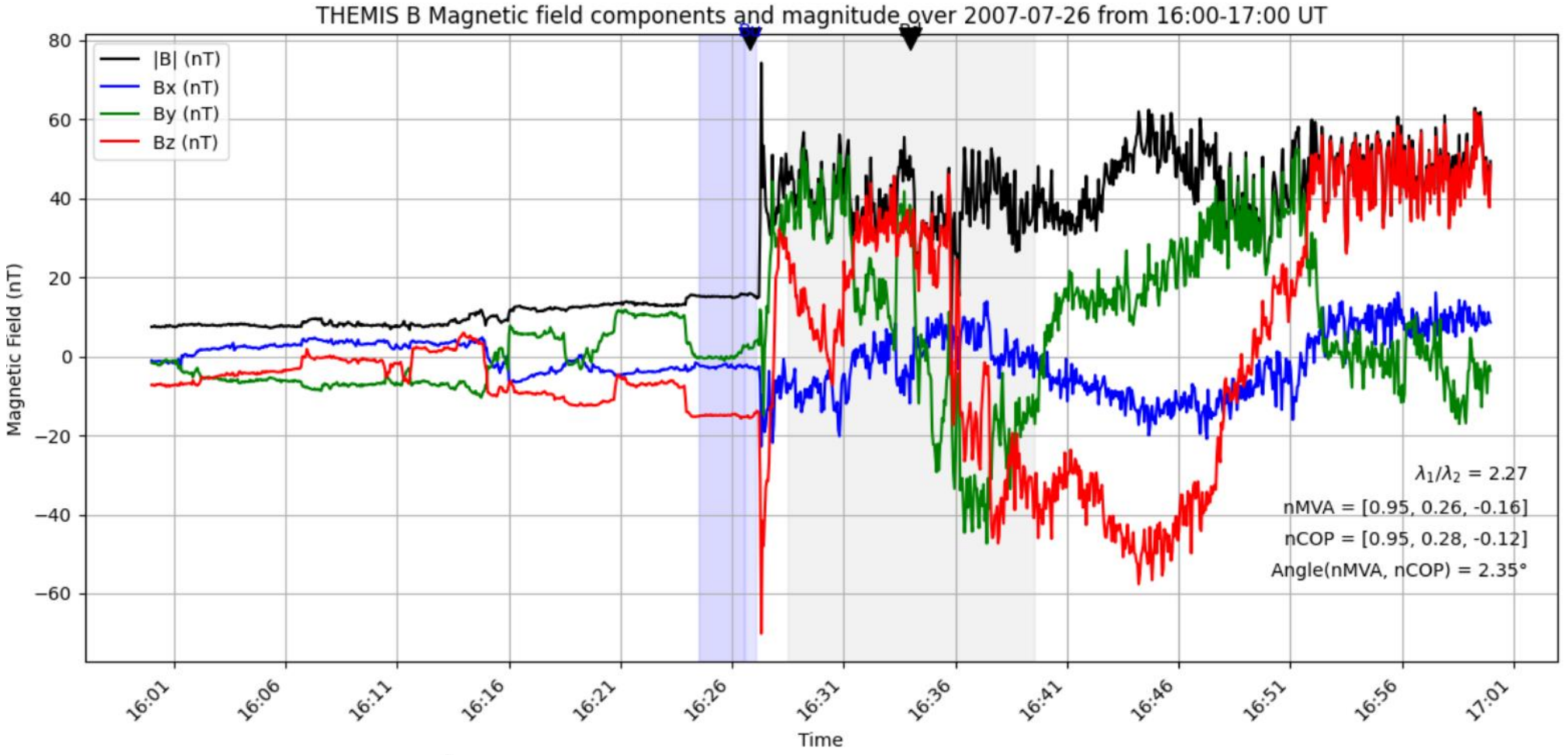
$$\mathbf{n}_{COP} = \frac{(\mathbf{B}_d \times \mathbf{B}_u) \times (\mathbf{B}_d - \mathbf{B}_u)}{|(\mathbf{B}_d \times \mathbf{B}_u) \times (\mathbf{B}_d - \mathbf{B}_u)|}$$

- Both methods are highly sensitive to the selected upstream and downstream intervals and the variability of the magnetic field.
- Both methods assume that the magnetic field is quite steady and the variations are slow and smooth.
- Therefore, we set the following requirements:
  - We apply both methods to the same upstream and downstream intervals and calculate the **n**MVA and **n**COP.
  - The ratio of the intermediate eigenvalue to the smallest eigenvalue should be greater than 2.
  - The angle between the normal vectors defined by the minimum variance analysis (MVA) and the magnetic coplanarity method must be less than 15 degrees.

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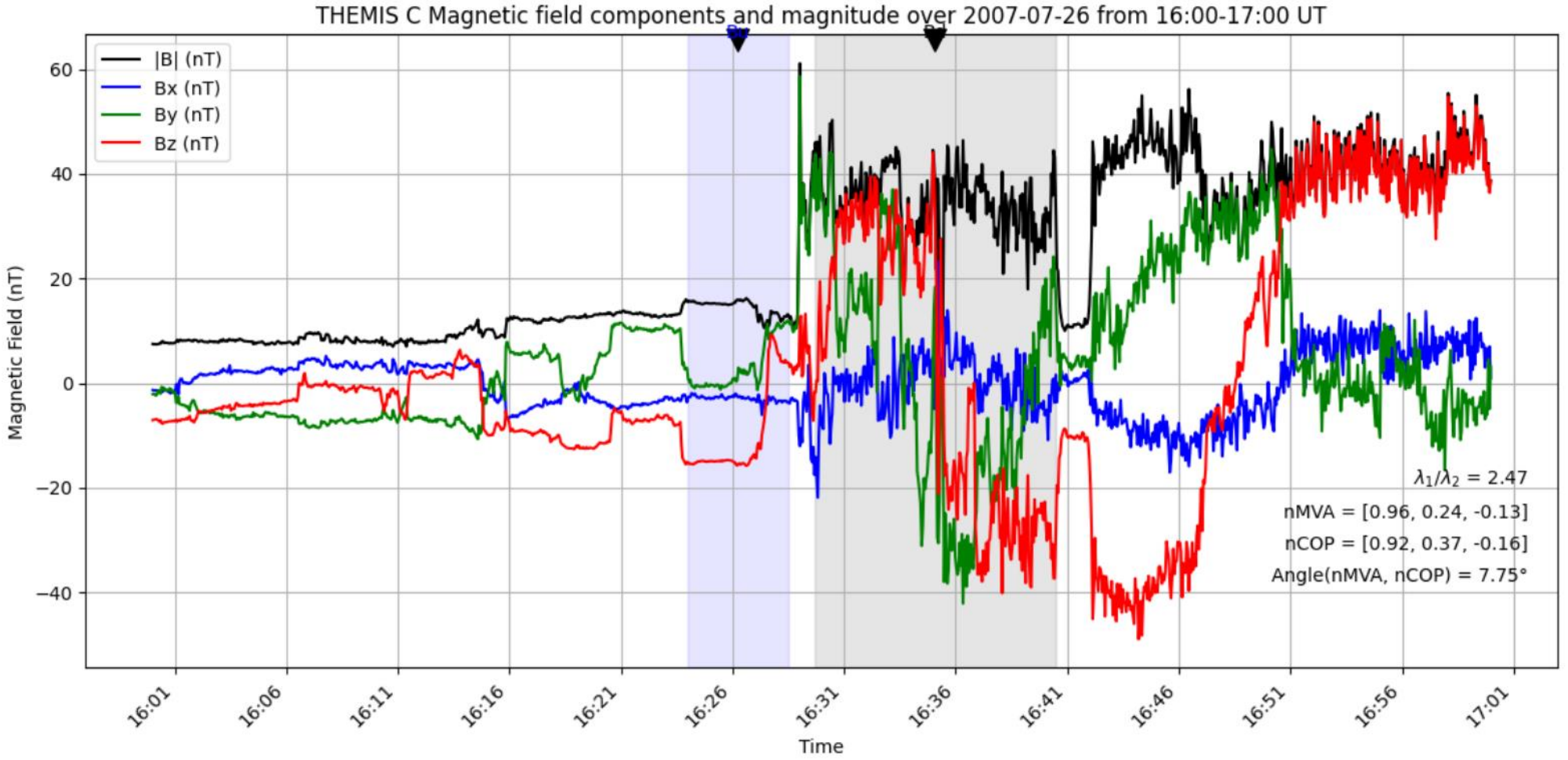
Bow Shock Normal Determination

- THEMIS B on July 26, 2007, from 16:20 to 16:40 (UT)



Bow Shock Normal Determination

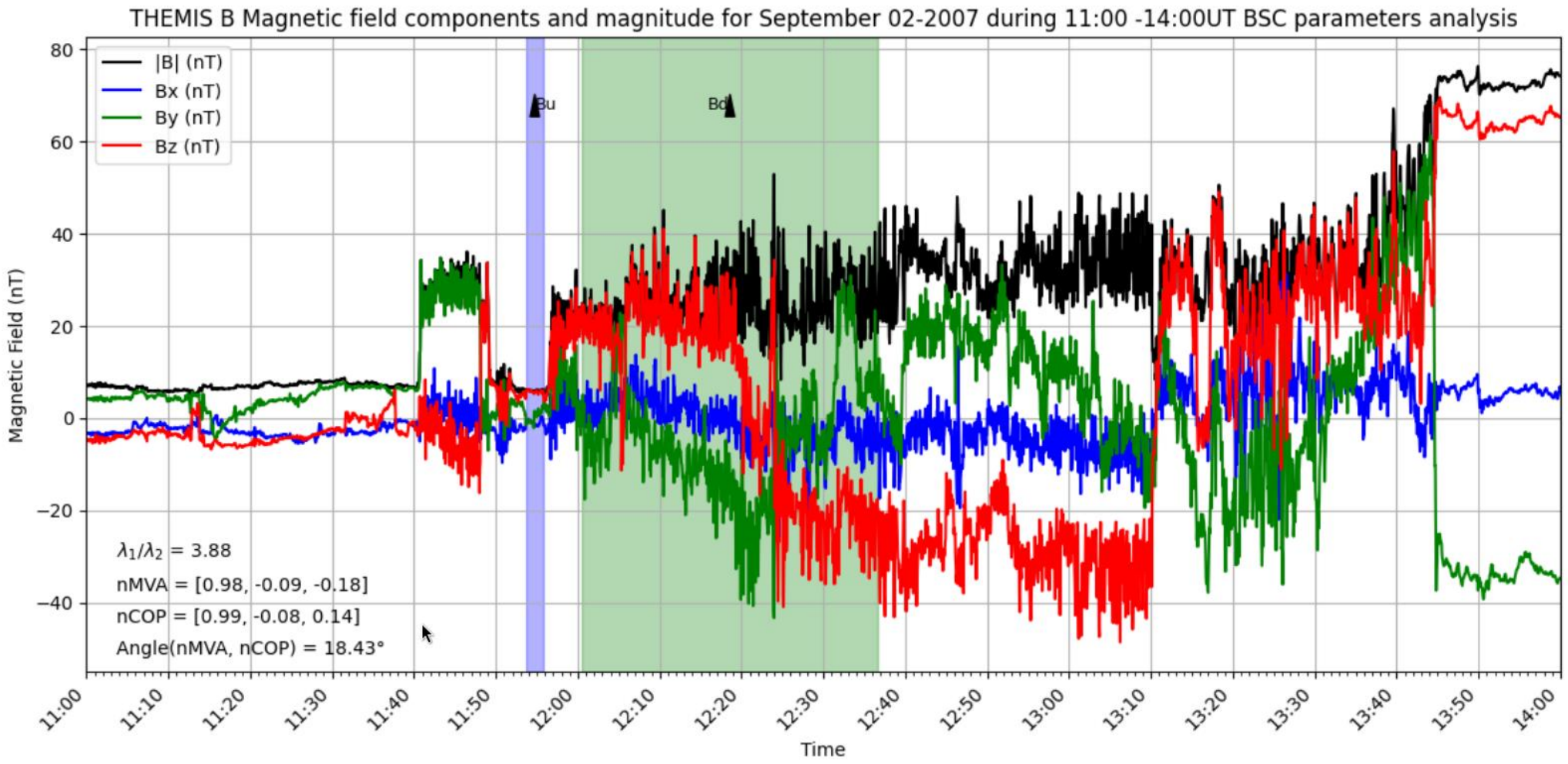
- THEMIS C on July 26, 2007, from 16:20 to 16:40 (UT)



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Bow Shock Normal Determination

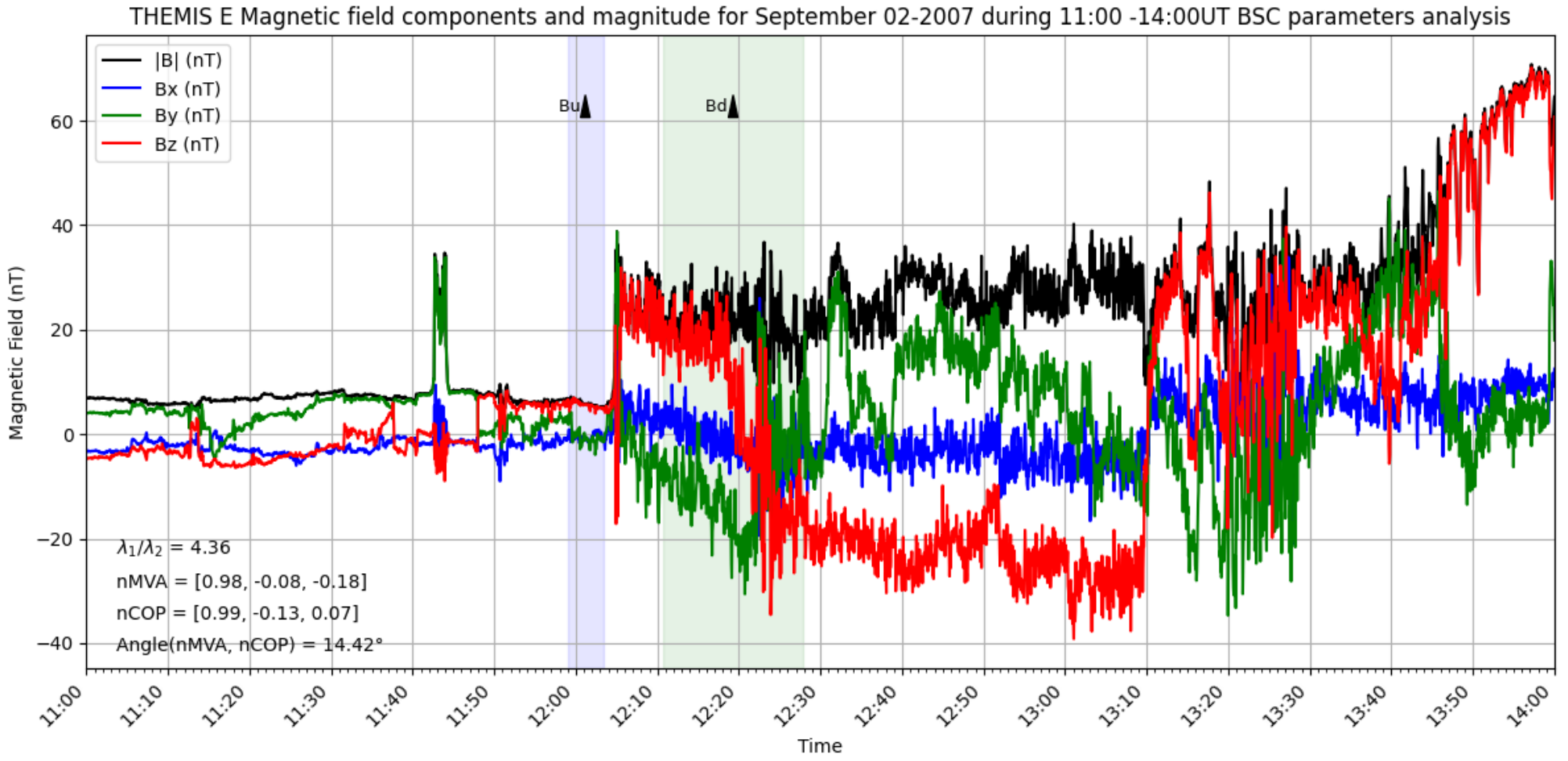
- THEMIS B on September 2, 2007, from 11:50 to 12:00 (UT)



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Bow Shock Normal Determination

- THEMIS E on September 2, 2007, from 12:00 to 12:10 (UT)



Discussion

- Single Spacecraft observations by THEMIS B and C on July 26, 2007, from 16:20 to 16:40 (UT)
  - We applied a Galilean transformation
  - Mass flux – OK
  - Momentum flux – OK
  - Electric field – Large Fluctuations
  - Magnetic flux – OK
- Single Spacecraft observations by THEMIS B and E on September 2, 2007, from 11:50 to 12:10 (UT)
  - TBD
- Rotational transformation is missing

Summary and Conclusion

- MHD/RH bow shock jump conditions were tested with three studies using single spacecraft observations.
- TWO events were selected from the THEMIS dataset.
- BS normals were determined by combining MVA and COP methods.
- After a Galilean transformation, good agreement was found in three out of four equations.
- If the single spacecraft analysis yields good results, we can include conjugate observations.
- Process multiple years of THEMIS observations in order to identify more favorable spacecraft configurations.
- Collect approximately 50-100 suitable bow shock events and perform a statistical study.

Thanks for your attention!

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