Reconstructing Global-scale Ionospheric Outflow With a Satellite Constellation

2017 Fall AGU Meeting

Abs. A41I-2398

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CLIMATE & SPACE Sciences & Engineering

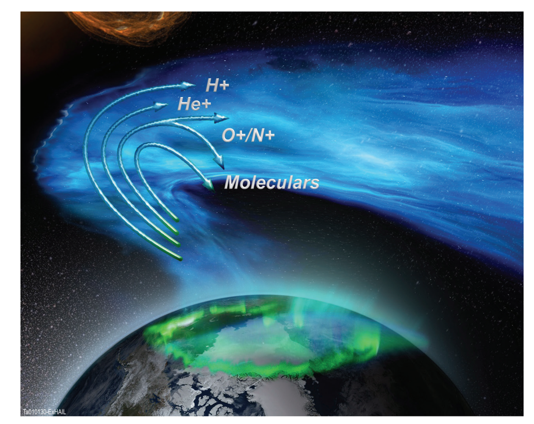
1. Motivation

- **Ionospheric outflow depletes Earth's atmosphere**
  - Releases 10^{24} – 10^{26} ions/s
  - That's a swimming pool per day, from a backyard pool to an Olympic-sized pool, depending on geomagnetic activity
- **One big unknown for geospace modeling: spatial distribution of ionospheric outflow**
  - We have flown single-spacecraft missions that have measured ionospheric outflow
  - We have empirical models of outflow patterns and relationships of total fluence-v-driving parameter
  - We don't actually know, however, what the ionospheric outflow pattern actually looks like at any given time
    - Requires a global view of this invisible population
    - Or a reconstruction from a fleet of satellites!
- **An open question:**
  - **How many satellites are needed to acurately reconstruct the instantaneous outflow pattern?**

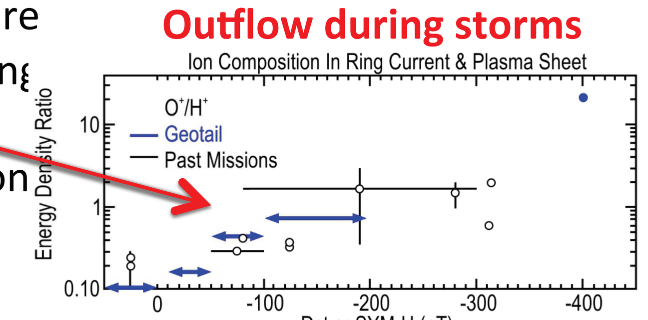
2. Outflow at Earth

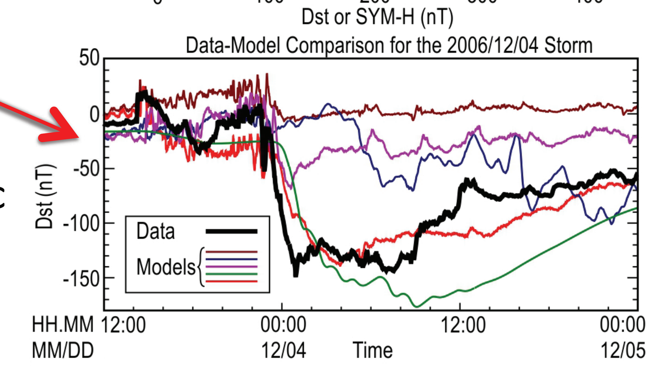
- Ionospheric outflow is strong from the cusp and auroral zone
- Several key species, like H^+ and O^+, with very different masses
- We have a decent handle on the physical processes of outflow
  - Of course, there is more to learn
- Composition of the magnetosphere dramatically changes during strong geomagnetic activity
- Inner magnetospheric composition shifts from H^+ dominance to O^+ dominance
- Models have mixed success at reproducing storm intervals
- One of the key unknown factors:
  - How much of the ionospheric material reaches the plasma sheet and contributes to the further storm development?

Colorful sketch of outflow



Outflow during storms

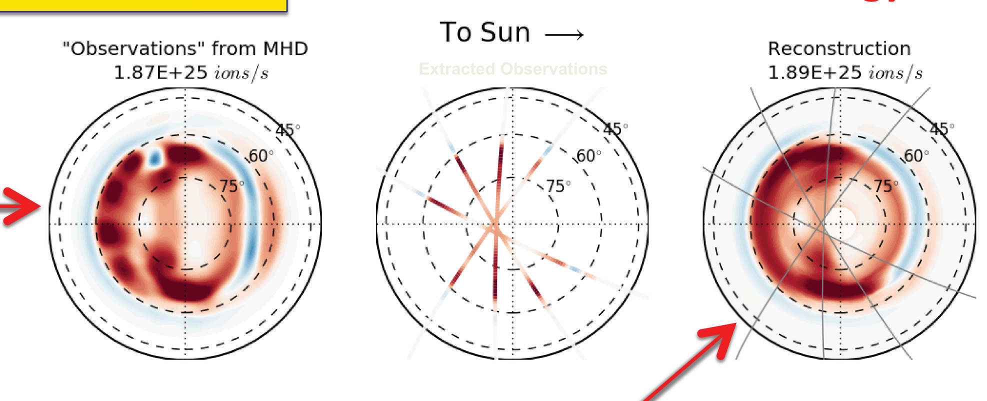




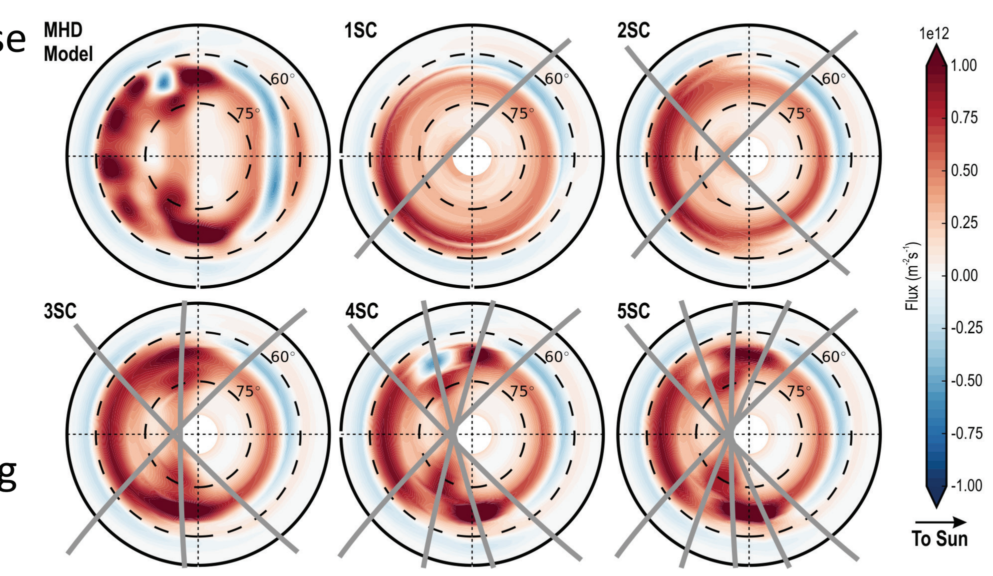
3. Reconstructing Outflow

- **Our reconstruction method:**
- Take a typical active-time outflow spatial pattern from an MHD storm simulation
- Map it to 1800 km altitude
- Extract values along one or more satellite trajectories
- Reconstruct the outflow pattern using only the extracted values
- We tried several interpolation methods, settling on Piecewise Cubic Hermite Interpolating Polynomials spline fitting
- Compare with original map
- **Statistics of reconstruction:**
- Do this for many trajectory parameter specifications
  - Local time of orbit crossing
  - Magnetic latitude of crossing
  - Nodal separation of the S/C
  - Number of S/C

Reconstruction methodology



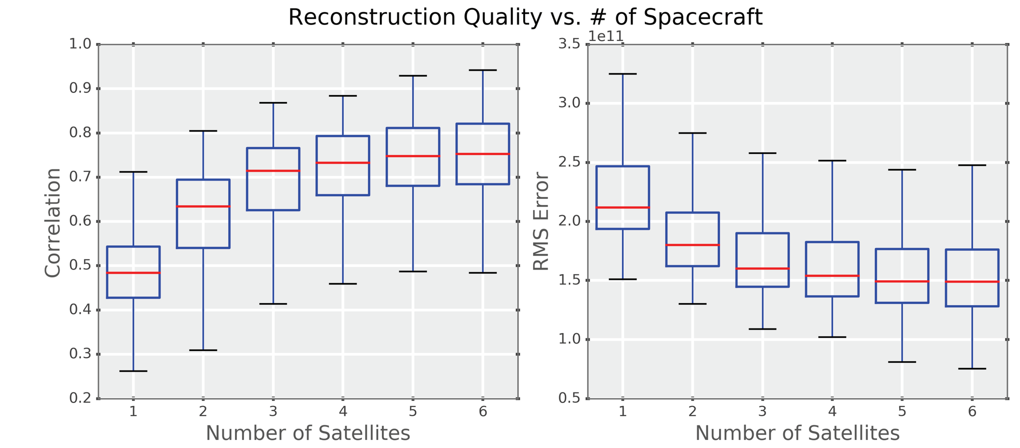
Reconstruction methodology



4. Quantifying the Fit

- In all, over 10,000 spatial reconstructions per MHD outflow spatial pattern plot (we considered several)
- Compared each 1˚x1˚ point above 60˚ magnetic latitude between reconstruction and original pattern
- Yields a scatterplot, from which two major values considered for the quantitative goodness of fit: **correlation** and **RMS error** from each comparison

Quantitative Goodness of Fit Analysis

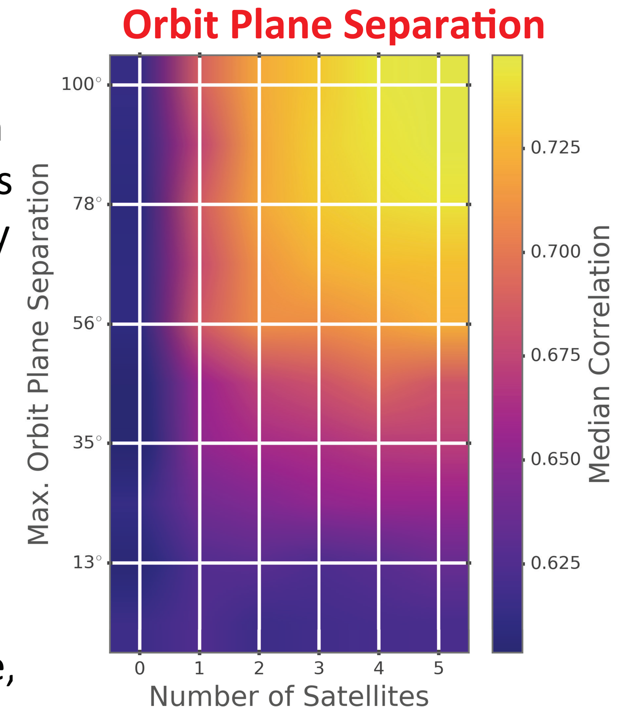


- Trend vs # of S/C seems to asymptote above ~4 S/C
- Correlation of 0.7 is good! This is a coefficient of determination (R^2) of 0.5 (50% of variance captured)

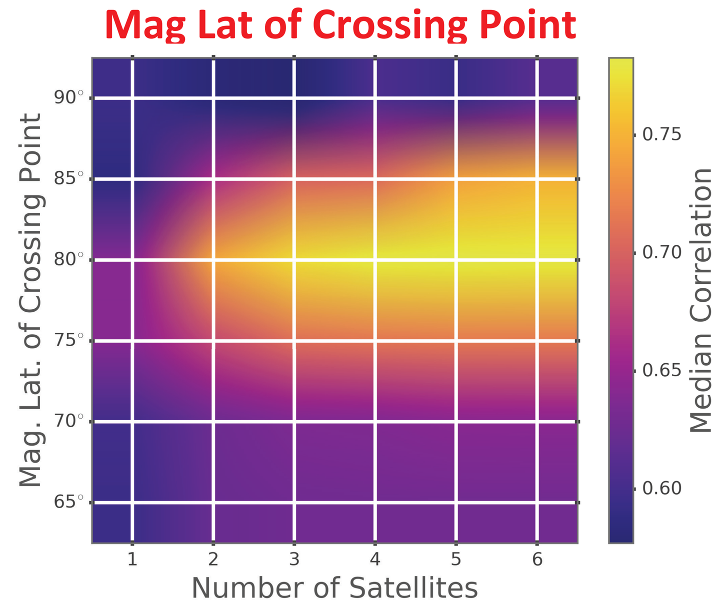
5. Outflow Reconstruction Optimization

- Categorize and subdivide the resulting values to look for optimal orbit configuration vs our parameters
- **The summary of findings:**
  - Adding S/C always helps, but with diminishing return
  - Increasing the maximum orbit plane separation helps
    - At least out to 100˚, what we covered in this study
    - Should decrease close to 180˚ as orbits overlap
  - There is a sweet spot for the maximum magnetic latitude of the orbit crossing point at ~80˚
    - This maximizes orbit dwell time in the auroral zone, where most of the outflow occurs
    - Too high and auroral zone dwell time is reduced
  - MLT of orbit crossing point did not matter much
    - There can be outflow "hot spots" at any local time, depending on the selected time

Correlation vs # S/C and Orbit Plane Separation

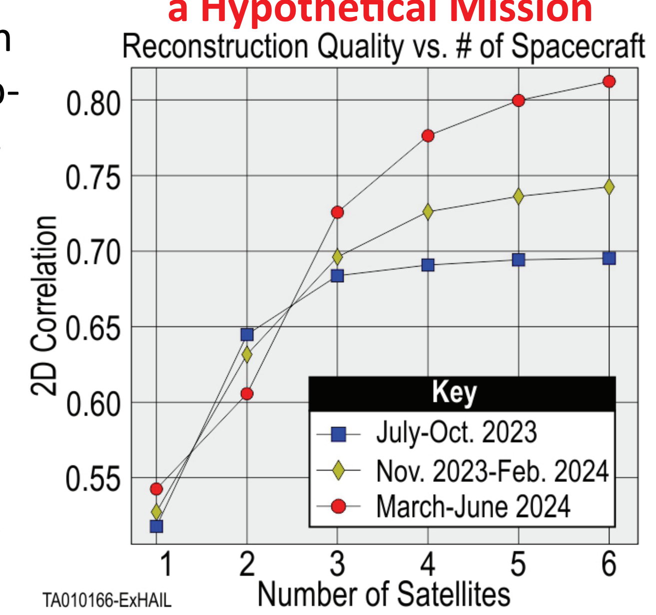


Correlation vs # S/C and Mag Lat of Crossing Point



- Hypothetical mission with a slowly-separating constellation at ~80˚ incl.
- Need ~10 months to reach R~0.7 and "good" correlations

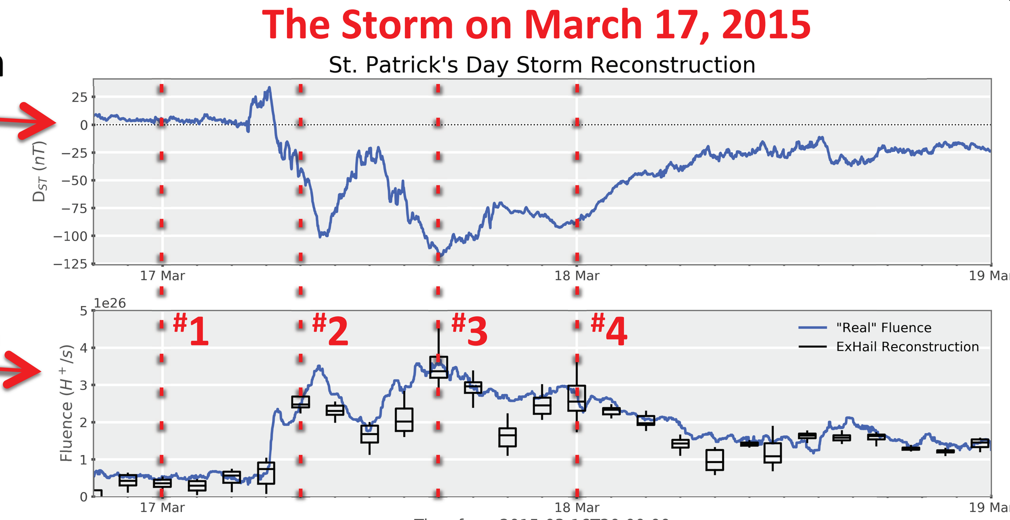
Correlation vs # S/C During a Hypothetical Mission

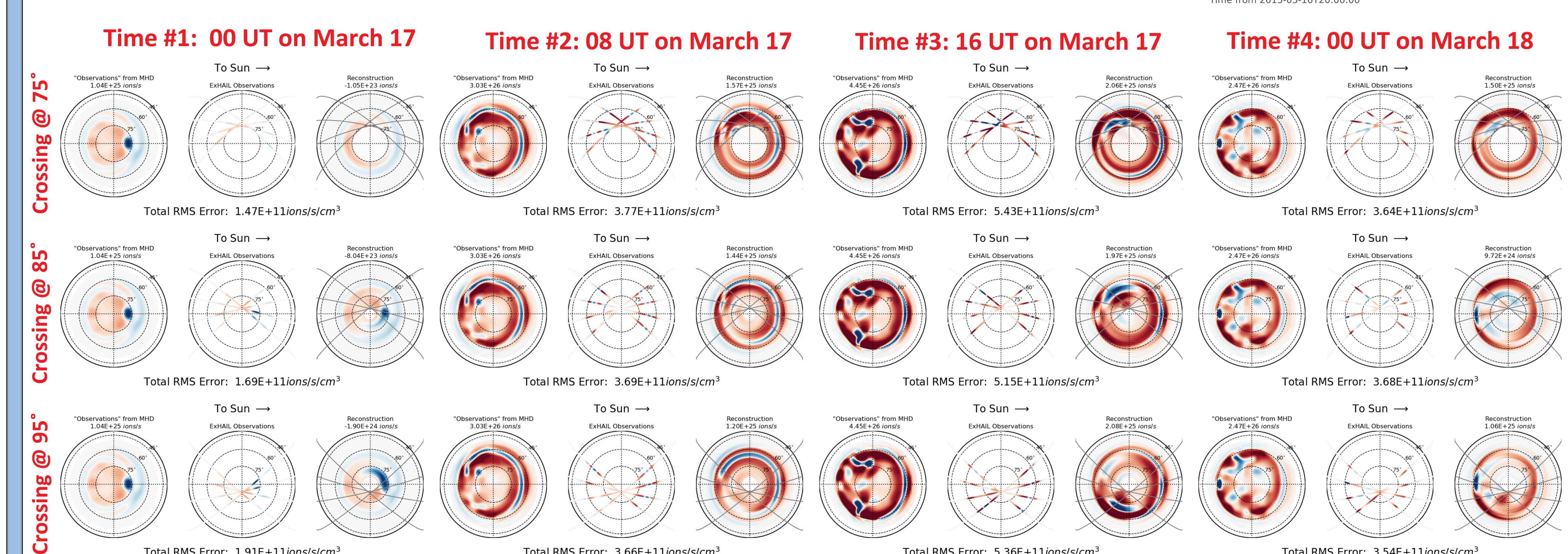


6. Outflow During a Storm

- Instead of a few idealized-input ionospheric outflow patterns, let's do a reconstruction vs time throughout a magnetic storm: **the March 2015 "St. Patrick's Day Storm"**
- Run the SWMF and extract outflow patterns *every minute* from MHD output
- To get statistics, vary the local time and magnetic latitude of the crossing, but with max orbit plane separation set at 90˚ (so, already at an "optimal" S/C spacing)
- Combine all reconstructions across 2-hour bins to calculate a total fluence comparison with original MHD outflow fluence time series
- Below, showing the reconstructions for 4 times during the storm, with 3 settings for the magnetic latitude of the crossing point: 75˚, 85˚, and 95˚ (as dipole "rocks")

The Storm on March 17, 2015





7. Conclusions

- We addressed the question of how many satellites would be needed to accurately (R~0.7) reconstruct the high-latitude ionospheric outflow pattern:

  Answer: 4

- Key findings of parameter study:
  - There is an optimal magnetic latitude of orbit crossing: **~80˚**
    - Maximize auroral zone obs.
  - There is a minimum to max orbit plane separation: **~60˚**
    - LT coverage is necessary
  - There is little-to-no influence on MLT of orbit crossing
    - Small outflow hot spots occur at all local times
- We simulated a storm interval:
  - With 4 well-separated, high-inc. S/C, the total fluence time series is well reconstructed
  - Spatial pattern reconstruction is "acceptable"
    - Some hot spots are missed