Reconstructing Global-scale Ionospheric Outflow With a Satellite Constellation

Michael Liemohn[1], Daniel Welling[1], Jorg-Micha Jahn[1], Philip Valek[1], Heather Elliott[1], Raluca Ilie[1], George Khazanov[1], Alex Glocer[1], Natalia Ganushkina[1], and Shasha Zou[1]

[1]Affiliation not available

November 22, 2022

Abstract

The question of how many satellites it would take to accurately map the spatial distribution of ionospheric outflow is addressed in this study. Given an outflow spatial map, this image is then reconstructed from a limited number virtual satellite pass extractions from the original values. An assessment is conducted of the goodness of fit as a function of number of satellites in the reconstruction, placement of the satellite trajectories relative to the polar cap and auroral oval, season and universal time (i.e., dipole tilt relative to the Sun), geomagnetic activity level, and interpolation technique. It is found that the accuracy of the reconstructions increases sharply from one to a few satellites, but then improves only marginally with additional spacecraft beyond ˜4. Increased dwell time of the satellite trajectories in the auroral zone improves the reconstruction, therefore a high-but-not-exactly-polar orbit is most effective for this task. Local time coverage is also an important factor, shifting the auroral zone to different locations relative to the virtual satellite orbit paths. The expansion and contraction of the polar cap and auroral zone with geomagnetic activity influences the coverage of the key outflow regions, with different optimal orbit configurations for each level of activity. Finally, it is found that reconstructing each magnetic latitude band individually produces a better fit to the original image than 2-D image reconstruction method (e.g., triangulation). A high-latitude, high-altitude constellation mission concept is presented that achieves acceptably accurate outflow reconstructions.

Reconstructing Global-scale Ionospheric Outflow With a Satellite Constellation

2017 Fall AGU Meeting

Abs. A41I-2398

Michael W. Liemohn

Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI USA liemohn@umich.edu

Coauthors: Dan T. Welling, Jörg-Micha Jahn, Phil Valek, Heather Elliott, Raluca Ilie, George V. Khazanov, Alex Glocer, Natalia Ganushkina, Shasha Zou

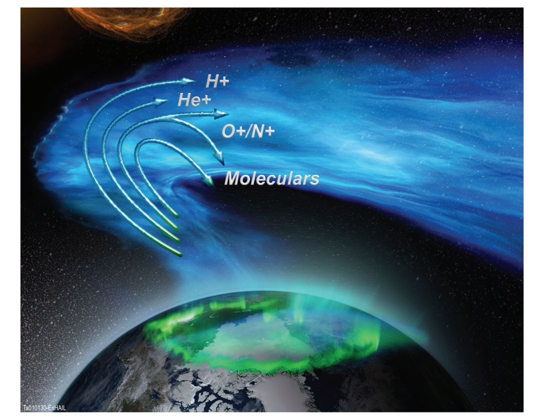
1. Motivation

- **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?**

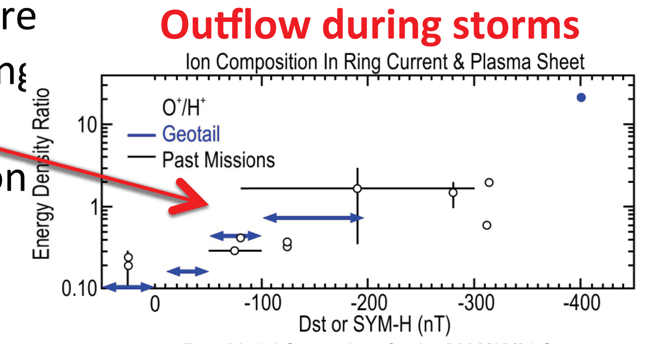
2. Outflow at Earth

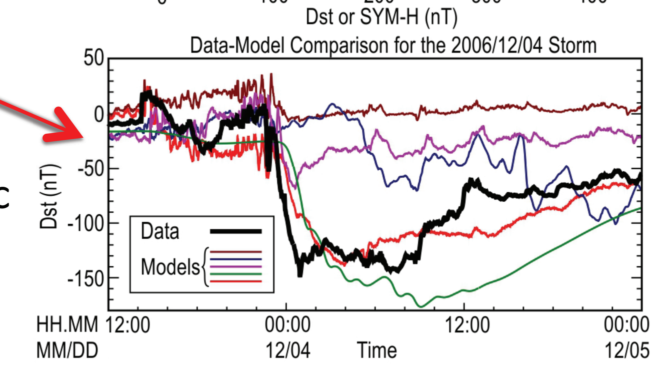
- Ionospheric outflow is strong from the cusp and auroral zone
- Several key species, like H^+ and O^+, with very different masses
- We have a decent handle on the physical processes of outflow
  - Of course, there is more to learn
- Composition of the magnetosphere dramatically changes during strong 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

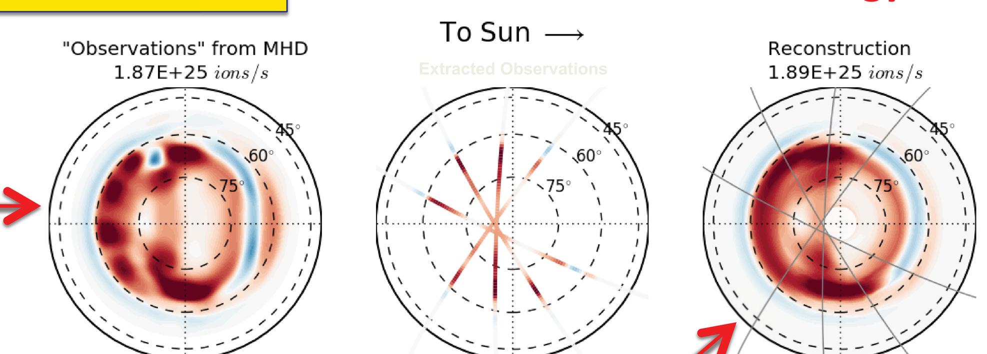




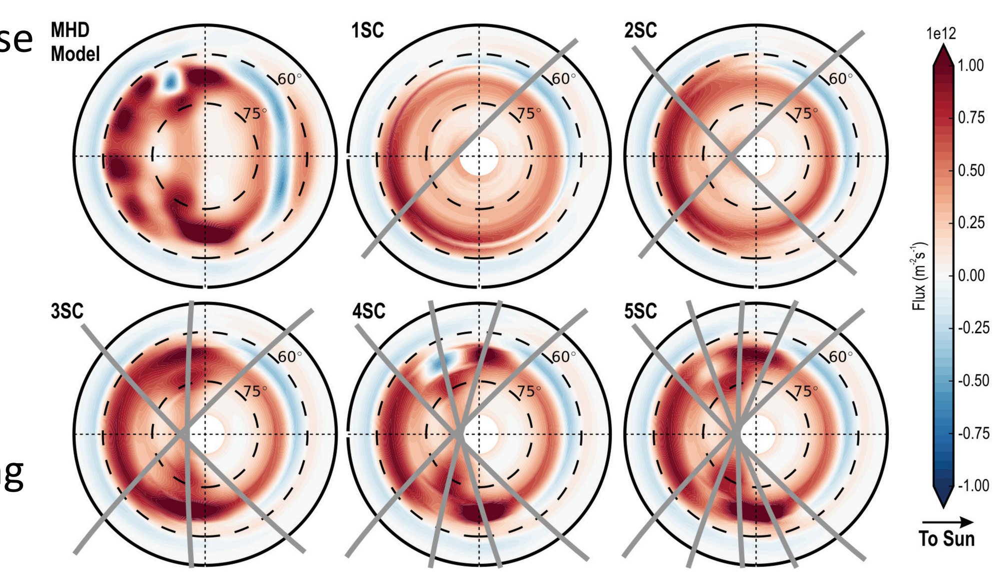
3. Reconstructing Outflow

- **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



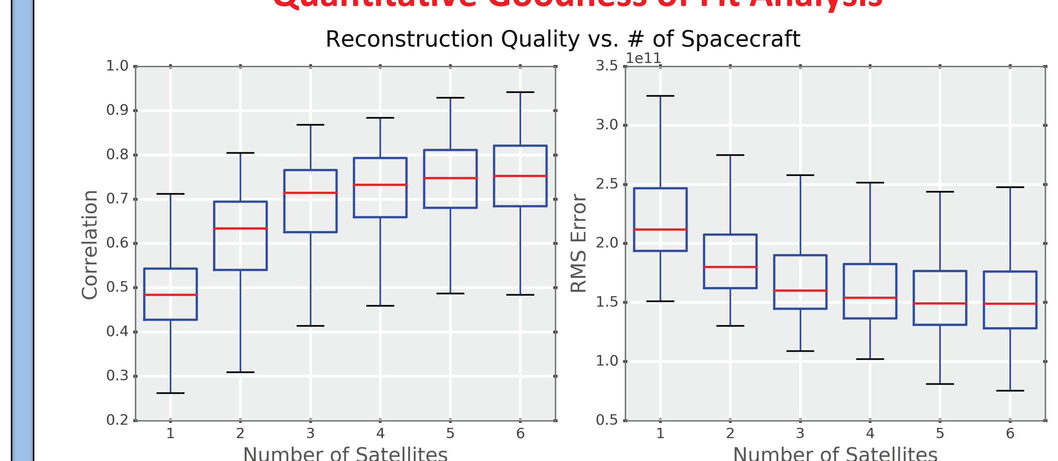
Reconstruction methodology



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

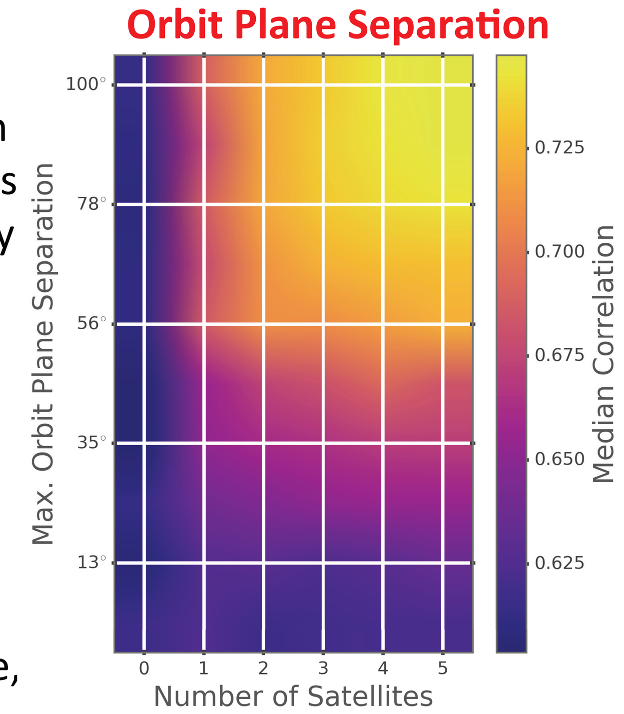


- Trend vs # of S/C seems to asymptote above ~4 S/C
- Correlation of 0.7 is good! This is a coefficient of determination (R^2) of 0.5 (50% of variance captured)

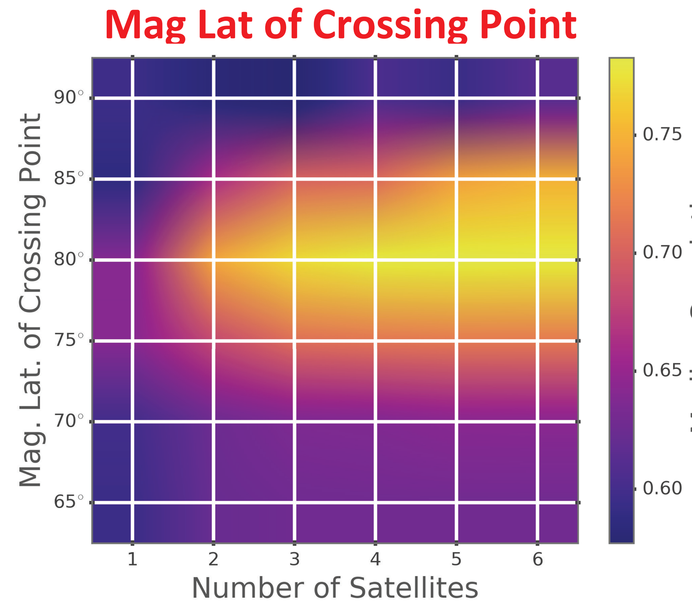
5. Outflow Reconstruction Optimization

- 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

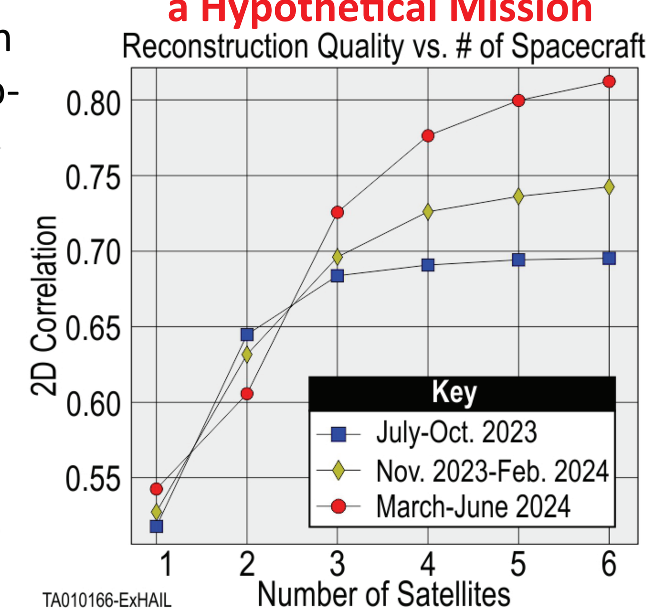


Correlation vs # S/C and Mag Lat of Crossing Point



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

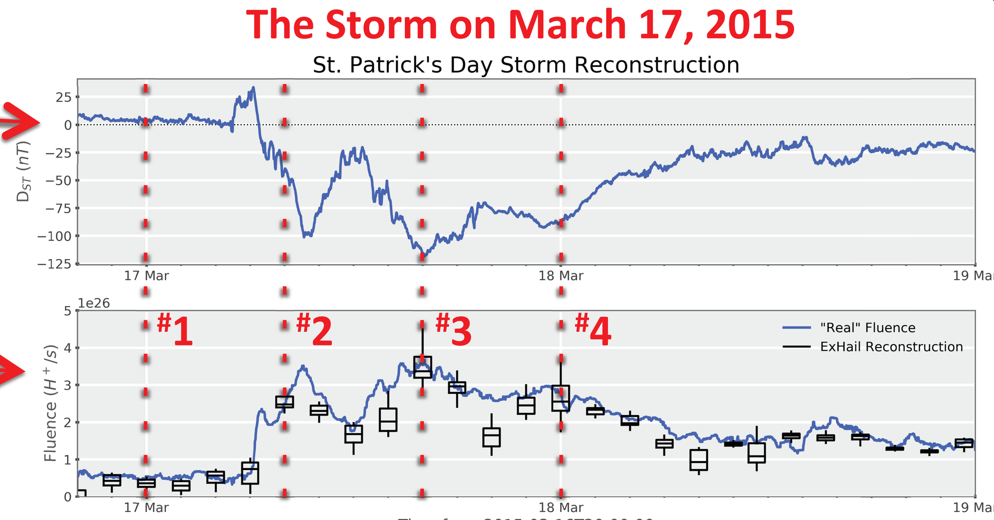
Correlation vs # S/C During a Hypothetical Mission



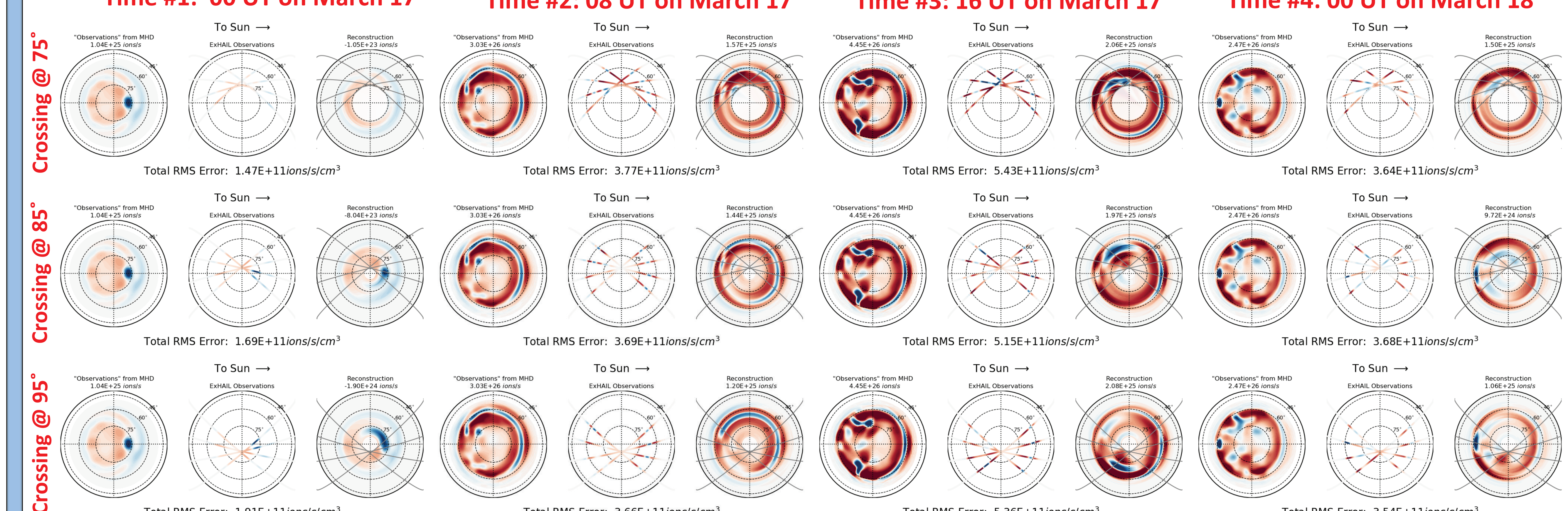
6. Outflow During a Storm

- 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



Time #1: 00 UT on March 17 | **Time #2: 08 UT on March 17** | **Time #3: 16 UT on March 17** | **Time #4: 00 UT on March 18**



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