Investigating Storm-Driven Thermospheric Density Enhancements with Two-Line Element Sets and Orbital Propagation

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Abstract

While flagship missions such as CHAMP and GOCE have shown us with accelerometer measurements that the thermospheric density in Low Earth Orbit (LEO) can increase by more than 200% during enhanced geomagnetic activity, current empirical models, such as those of the MSISE and Jacchia families, as well as the Drag Temperature Model, fail to reproduce this behavior, limiting the ability to perform orbit prediction and space situational awareness. Several methods have been employed to address this dilemma. One is the High-Accuracy Satellite Drag Model (HASDM), which uses its Dynamic Calibration Atmosphere to employ differential correction across 75 spherical calibration satellites to generate correction parameters to the density that are related to 10.7 cm solar radio flux and ap (Storz et al. 2005). Doornbos et al. 2008 has implemented a method that estimates height-dependent scale factors to the densities from empirical models with respect to densities directly derived from two- line element sets (TLEs). HASDM's reliance on Space Surveillance Network observations limit its accessibility and detail, and Doornbos' methods are limited by the fact that TLEs are mean elements; densities derived from them are subject to errors due to smoothing over an entire orbit. In addition, the method of deriving densities from TLEs was initially done only to provide inputs to the SGP4 orbital propagator, which was initially developed without consideration of solar radiation pressure on the trajectory of modeled spacecraft. We present a method to generate new model densities during geomagnetic storms by using an in-house orbital propagator, the Spacecraft Orbital Characterization Kit (SpOCK). This method estimates and applies scale factors to F10.7 and a p to minimize orbit propagation errors with TLEs. The method is tested on a variety of satellites, including CHAMP, GOCE, and the CubeSats of the QB50 and FLOCK constellations. This method proposes to grant insight into storm-time thermospheric density enhancement by modeling the effects of storms on the drag of numerous LEO spacecraft, increasing our understanding of thermospheric dynamics and granting us improved tools for space traffic management and thermospheric research.

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INTRODUCTION

Thermosphere Dynamics

- Neutral densities increase up to 800% during geomagnetic storms[4].
- Satellite two-line element sets (TLEs) show increased orbital decay during geomagnetic storms from increased drag[2].

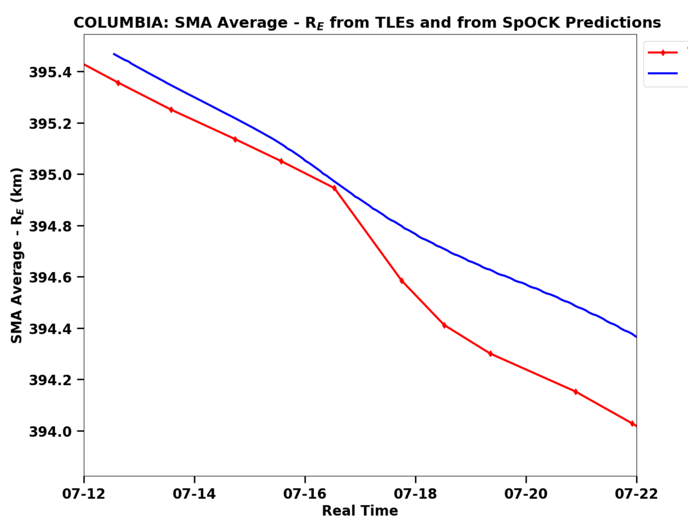

Figure 1: SpOCK inaccurately modeling orbital decay of the Columbia CubeSat.

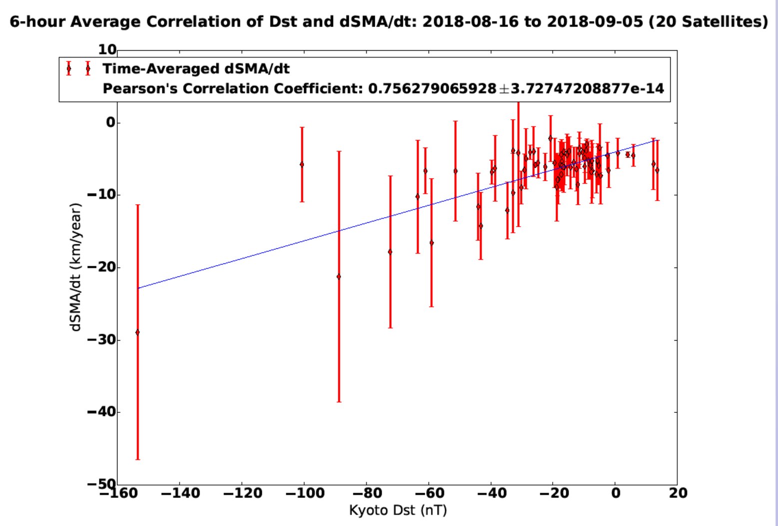

Figure 2: The strongly positive correlation between rate of deorbit and geomagnetic activity indicated by Dst for 20 identical Flock 2K CubeSats.

Weakness of Empirical Atmospheric Models

- Models like NLRMSISE-00 (Picone et al. 2002) poorly reproduce the storm-time density increase.
- Poor model performance reduces accuracy of orbital propagators (Figure 1) like UofM's Spacecraft Orbital Characterization Kit (SpOCK)[1].

Model Correction

- High-Accuracy Satellite Drag Model (HASDM) used by USAF to correct Jacchia-1970[6].
- HASDM Dynamics Calibration Atmosphere (DCA) uses Space Surveillance Network data of >75 orbiting spheres to estimate corrections to F10.7 and a_p[6].
- Doornbos et al. 2008 used TLEs to estimate corrections but assumed TLE-derived densities were sufficient[3].
- We propose a method that estimates corrections by minimizing orbit error between SpOCK orbits and TLEs.

OBJECTIVES

- Develop an algorithm capable of **estimating corrections to empirical model densities** during geomagnetic storms.
- **Validate** the corrected densities returned by the algorithm in comparison to *in-situ* densities measured by the SWARM spacecrafts.
- Demonstrate the algorithm's **self-consistency** across a wide variety of modeled spacecraft orbits during different storms.
- Demonstrate the efficacy of using **orbit error minimization** to back out corrected densities from empirical atmospheric models.

METHODOLOGY

<u>Multifaceted Optimization Algorithm:</u>

Corrects NRLMSISE-00 model densities:

1. **Area Optimization Algorithm (AROPT):**
   - Loop over preceding quiet time and adjust cross-sectional area until orbit error is minimized.
2. **F10.7 Optimization Algorithm (FOPT):**
   - Obtain the **mean** of the optimized area distribution (<u>assumes NLRMISISE-00 underpredicts effects from storms</u>)
   - Repeat the loop, adjusting F10.7 until orbit error is minimized; retrieve the F10.7 correction for each interval.
3. **Applying Corrections:**
   - Linearly interpolate median corrections across all satellites.
   - Apply corrections to F10.7 inputs to NRLMSISE-00 along-track the orbits of validation spacecraft.
   - Compare the resulting densities to *in-situ* measurements.

<u>Scenario:</u>

- Time: 2018-08-21 and 2018-08-31
- Calibration Targets: 10 Flock 2K satellites
- Validation Satellites: SWARM-A, -B, -C

<u>Note:</u> Chosen quartile of the optimized area distribution strongly impacts corrections. Best results when correcting NASA OMNIWeb inputs (static daily indices).

Figure 3: An example of a Flock 2K 3U CubeSat launched by Planet Labs, Inc.

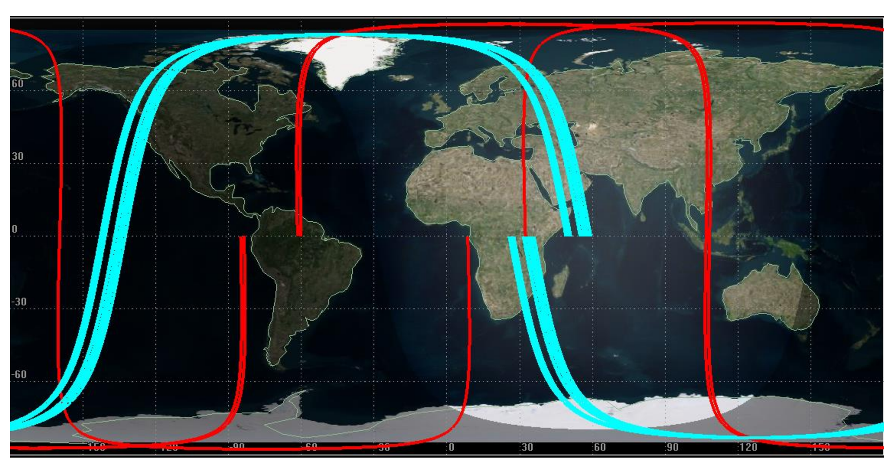

Figure 4: Orbits of the Flock 2K CubeSats (cyan) and of SWARM (red) in the August 2018 storm.

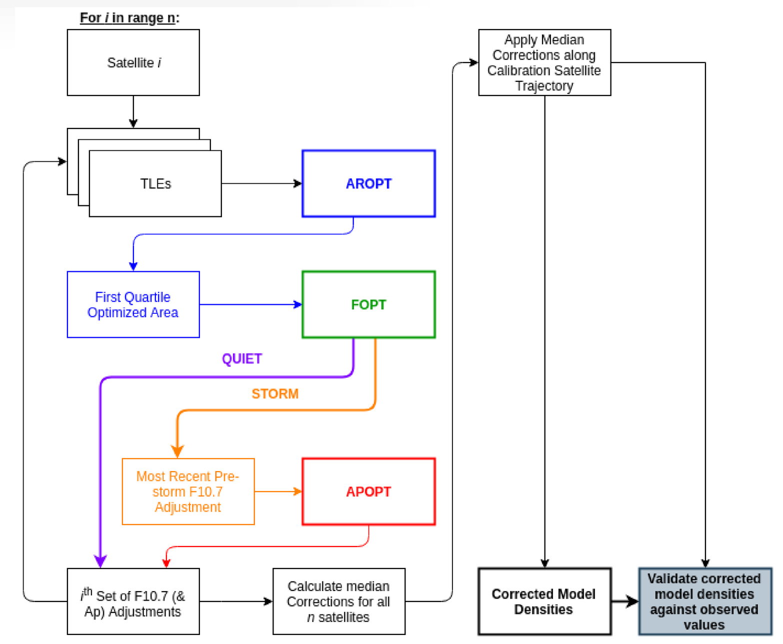

Figure 5: A flowchart of the MOA algorithm. We restricted ourselves to the AROPT and FOPT sub-processes for this initial study.

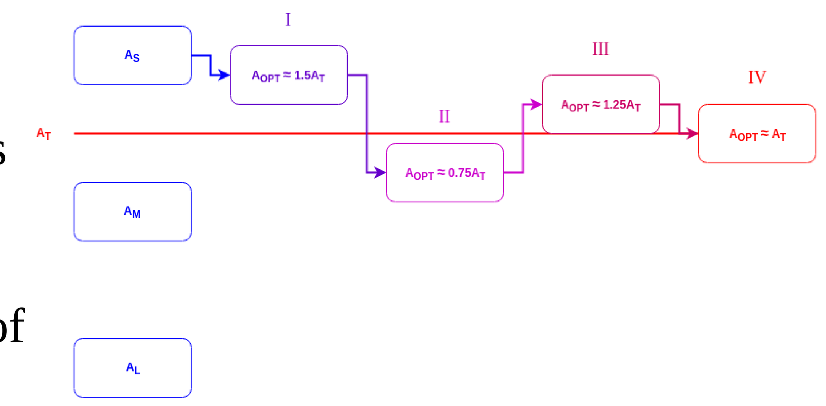

Figure 6: A flowchart of the bracketing processes used by AROPT to find the optimized area.

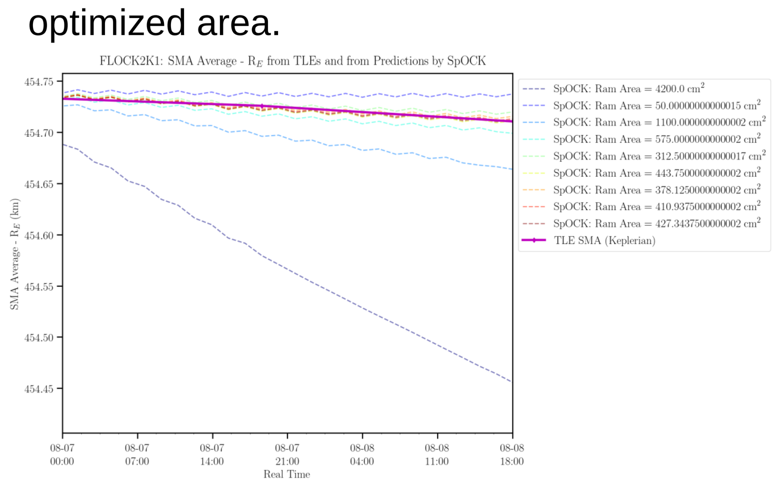

Figure 7: AROPT optimizing the area of the Flock 2K 1 satellite.

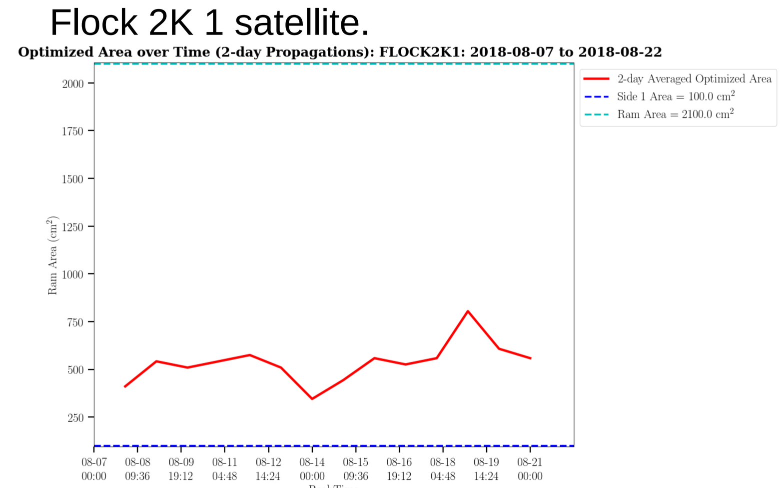

Figure 8: AROPT's resulting optimized areas for Flock 2K 1 during quiet time.

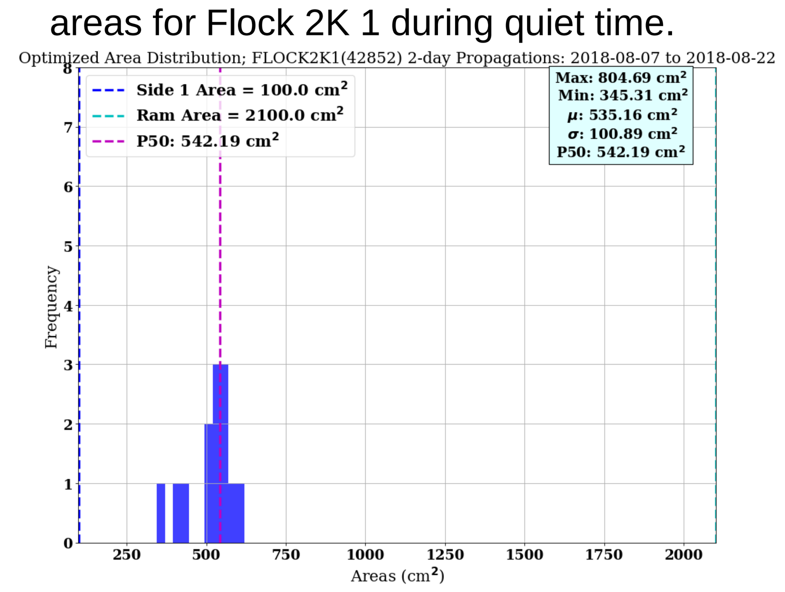

Figure 9: Flock 2K 1 optimized areas during quiet time assembled into a histogram.

RESULTS

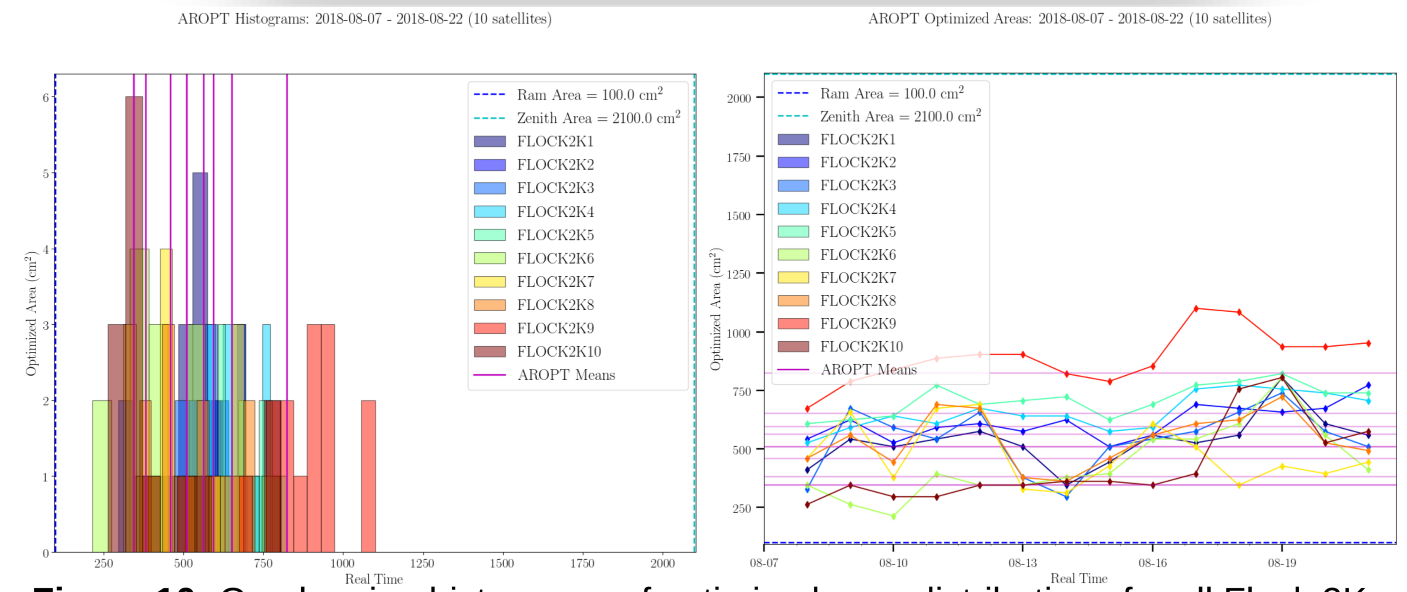

Figure 10: Overlapping histograms of optimized area distributions for all Flock 2K satellites (left) and their corresponding optimized areas over time (right)..

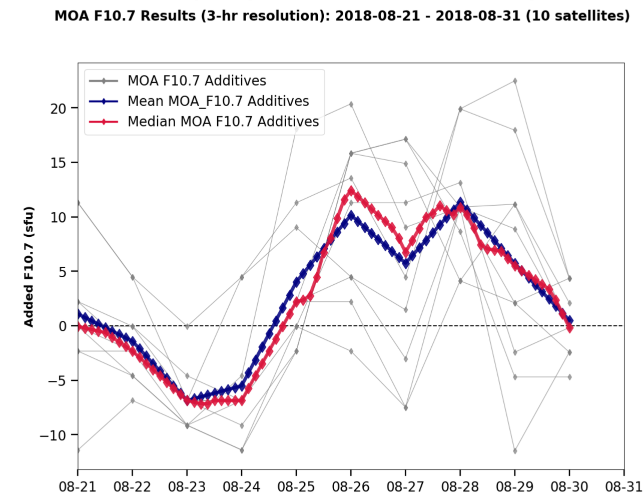

Figure 11: Linearly-interpolated F10.7 corrections across all 10 satellites.

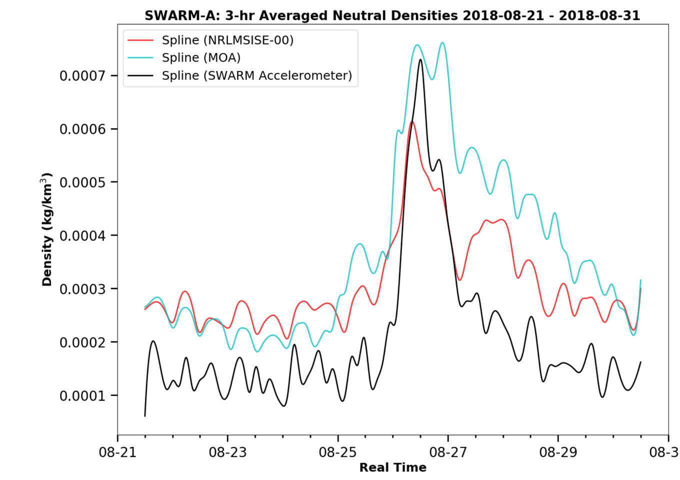

Figure 12: Corrected densities along-track SWARM-A.

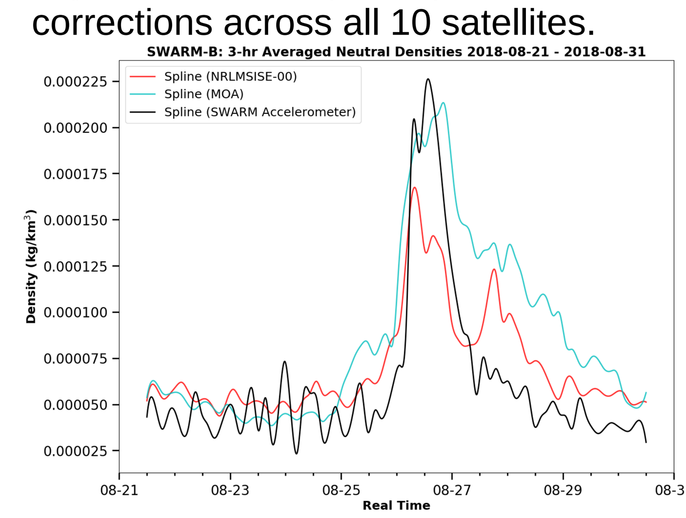

Figure 13: Corrected densities along-track SWARM-B.

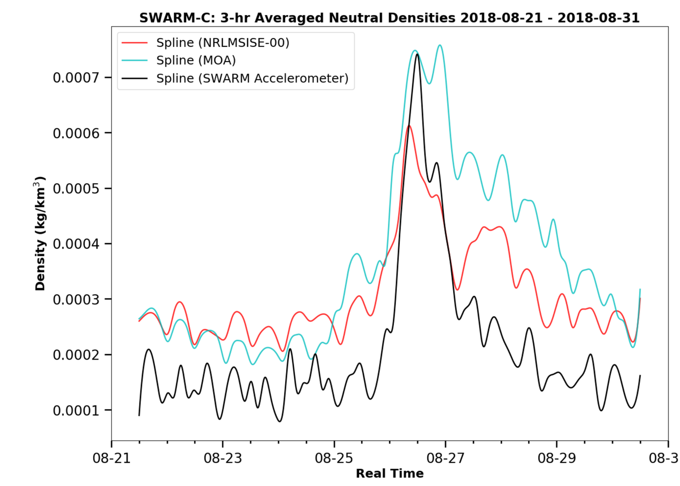

Figure 14: Corrected densities along-track SWARM-C.

DISCUSSION AND FUTURE WORK

- Density correction allowing for reductions up to 10% error in magnitude, on par with results obtained by Doornbos et al. 2008.
- Post-main phase corrected densities are consistently too large.
- Densities more accurate than NLRMSISE-00 during initial onset.
- Raw corrected densities exhibit much greater amplitude variation compared to SWARM.
- Must validate the algorithm in other storms of varying intensities and using a variety of other calibration targets.
- Incorporate the third sub-process of correcting 3-hr a_p during storm main phase.

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