Orbital Decay Estimation of Satellites Using Drag Analysis During Geomagnetic Storm

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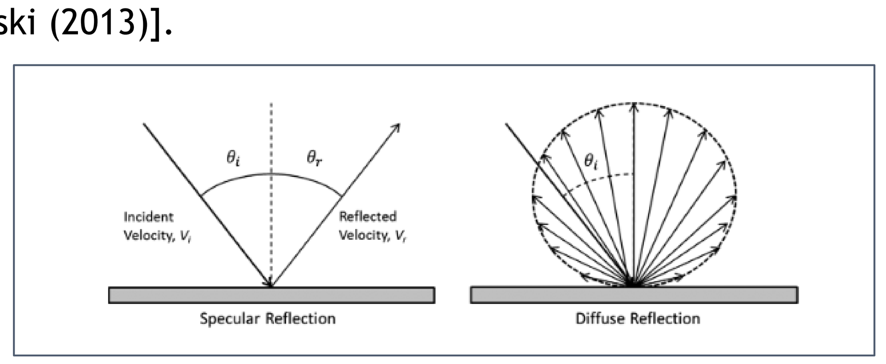
ABSTRACT

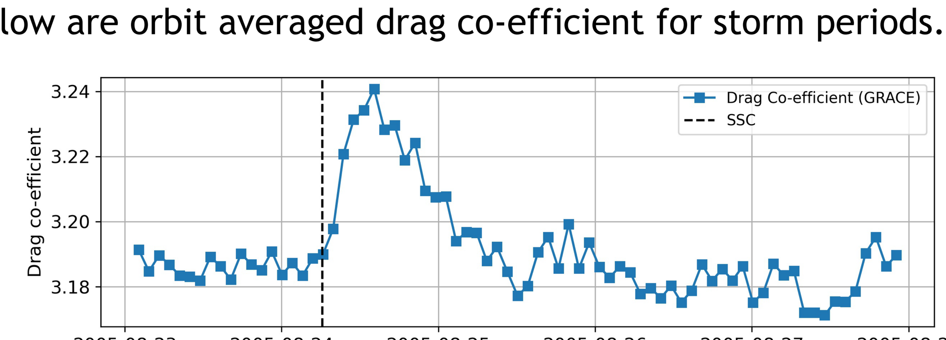
Regular orbit propagation methods are used to determine satellite co-ordinates. In particular, the Simplified General Perturbation method (SGP4) is used with NORAD two element sets (TLEs). However, SGP4 uses a constant drag term (B^*) term which does not consider the variation in atmospheric drag. As a result, SGP4 incurs significant error in estimating orbit ephemerides for long term propagation. In this work, we have provided atmospheric drag analysis of CNOFS and GRACE during Sep 2011 and Aug 2005 geomagnetic storms respectively. A gas-surface interaction model called Diffused Reflection with incomplete accommodation (DRIA), has been used on a simplistic configuration of the satellites to calculate normalized drag co-efficient. Using drag analysis results, we have calculated estimated storm-time orbital decay (SOD) of the satellites during selected storm periods. The results show increased decay rate during peak phase of the storms and subsequently, a higher orbital decay compared to quiet time. A comparison with semi-major axis decay from regular SGP4 propagation shows a significant difference as storm progresses and eventually matches during recovery phase.

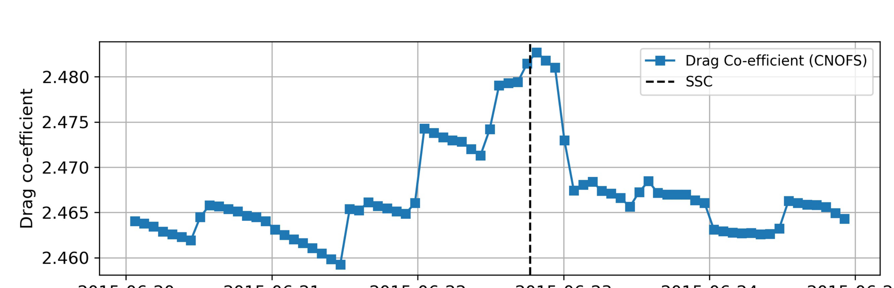
DRAG ANALYSIS

- Drag co-efficients(C_D) are calculated using a gas-surface interaction model called DRIA (Diffused reflection and incomplete accommodation). It considers **random thermal motion** of incident particles and assumes a **diffused reflection** with a Maxwell-Boltzmann distribution for velocity of the reflected particles [Pilinski (2013)].

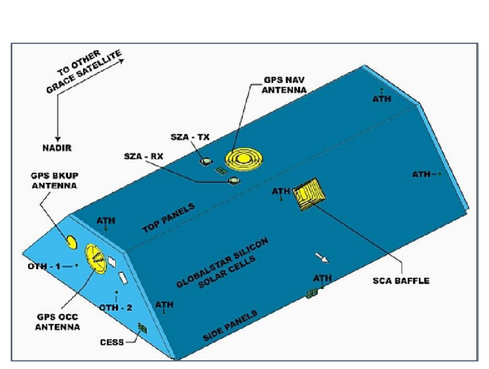


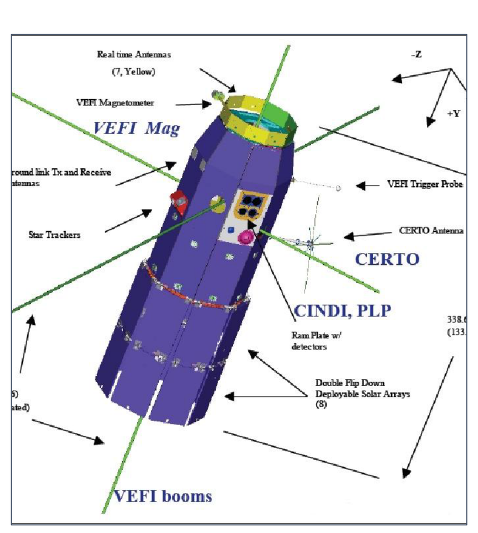
- Normalized drag coefficients (C_D) for satellite geometries are derived from Sentman's(1961) calculation of drag for diffused reflection in free molecular flow. Energy accommodation co-efficient is α = 0.93 [Sutton (2009)]. C_D is averaged over all atmospheric elements according to their mass fraction. Plots shown below are orbit averaged drag co-efficient for storm periods.





GRACE and CNOFS model used for drag-calculation





ORBITAL DECAY

The satellite storm-time orbital decay(SOD) is given by the expression *[Chen et al(2012)]*:

$$\frac{da}{dt} = -C_D \frac{A}{m}\sqrt{GM\langle a\rangle}\,\rho \qquad \left(\frac{da}{dt}\right)_b = -C_D \frac{A}{m}\sqrt{GM\langle a\rangle}\,\rho_b$$

Where, $\frac{da}{dt}$ = orbital decay rate, $\left(\frac{da}{dt}\right)_b$ = background decay rate.

C_D = drag co-efficient, A = effective s/c cross section, m = s/c mass, G = gravitational constant, M = mass of earth, $\langle a\rangle$ = daily averaged semi-major axis, ρ = neutral density, ρ_b = quiet-time density.

Orbital Decay is obtained by integrating decay rate over time:

$$\Delta a = \int \frac{da}{dt} = -C_D \frac{A}{m}\sqrt{GM\langle a\rangle}\int \rho dt \qquad (\Delta a)_b = \int \left(\frac{da}{dt}\right)_b = -C_D \frac{A}{m}\sqrt{GM\langle a\rangle}\int \rho_b dt$$

- Neutral density for normal and quiet-time condition is calculated using Jacchia-Bowman(2008) empirical atmospheric model.
- Orbital decay (Δa) in both cases are almost equal to background decay before the shock arrives, however the difference between the two starts increasing during the main phase of the storm.
- Semi major axis decay from SGP4 shows a linear decay with shifts at TLE epochs, which agrees well with orbital decay before storm but incurs significant difference as the storm progresses.

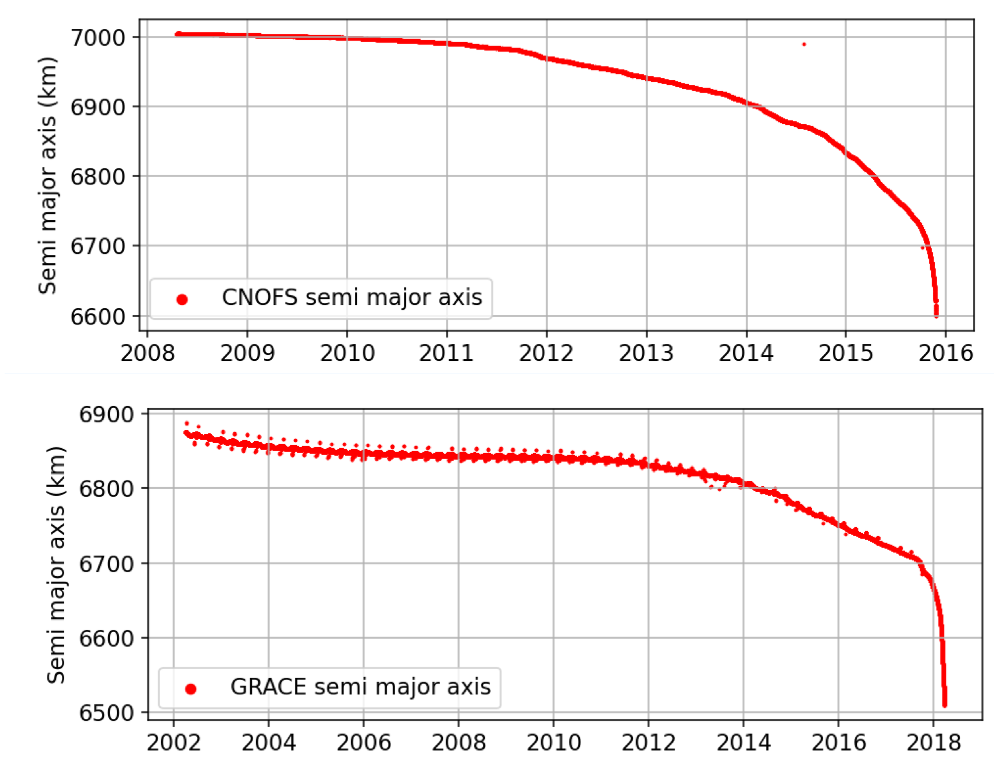


Figure: Semi-major axis of CNOFS (top) and GRACE (bottom) shows the decay of a satellite orbit with time

RESULTS

CNOFS

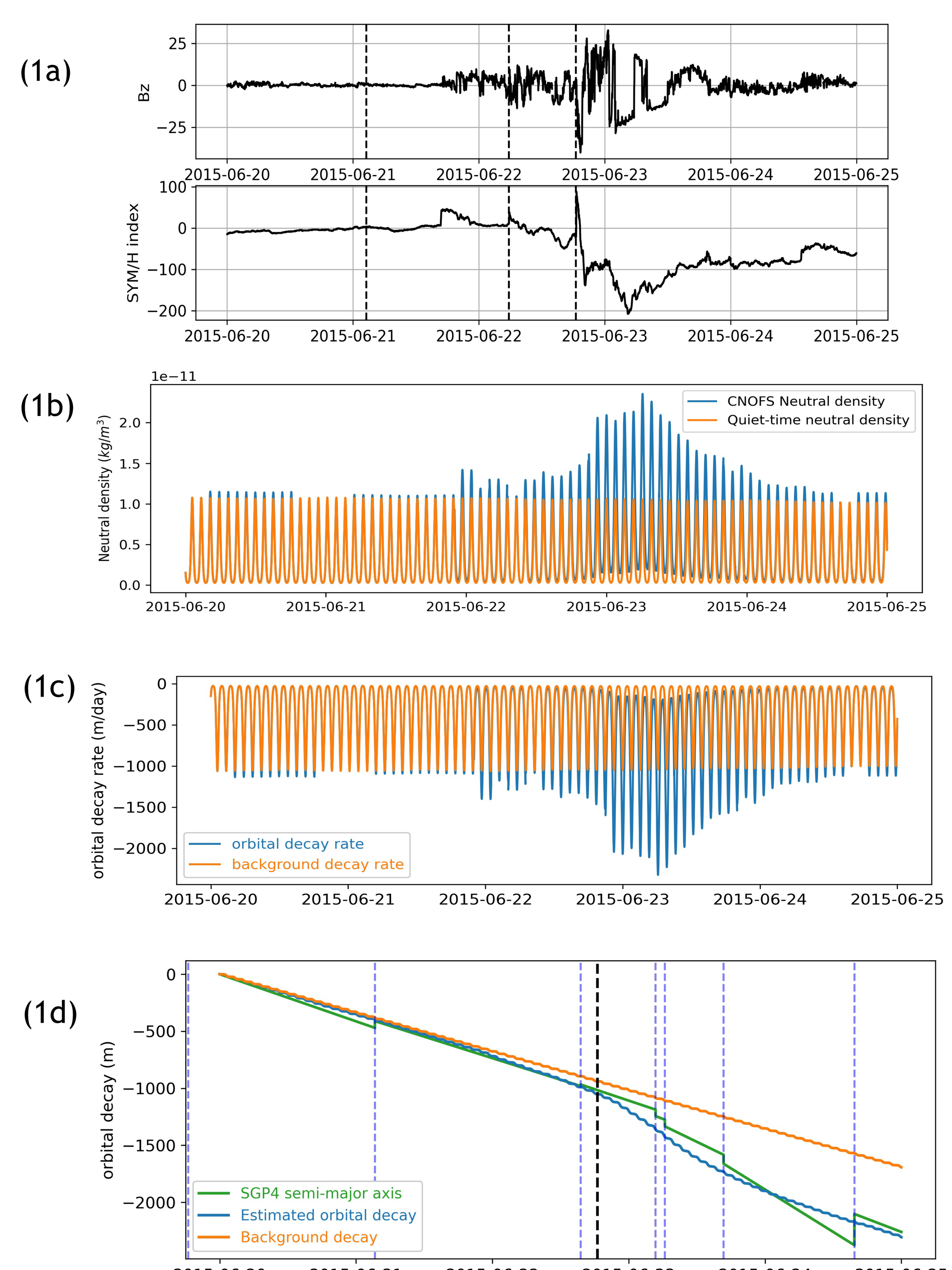


Figure (1a) IMF B_z and SYM-H index for June 20-25, 2015, Vertical dashed lines shows shock impact of CME. First two shocks creates minor storms, 3rd one at June 22 18:30 UT is the most important impact. (1b) Neutral mass density data for CNOFS, (1c) storm-time orbital decay rate and (1d) orbital decay compared with SGP4 semi major axis decay. TLE epochs are denoted by purple dashed lines. Black dashed line represents sudden storm commencement.

GRACE

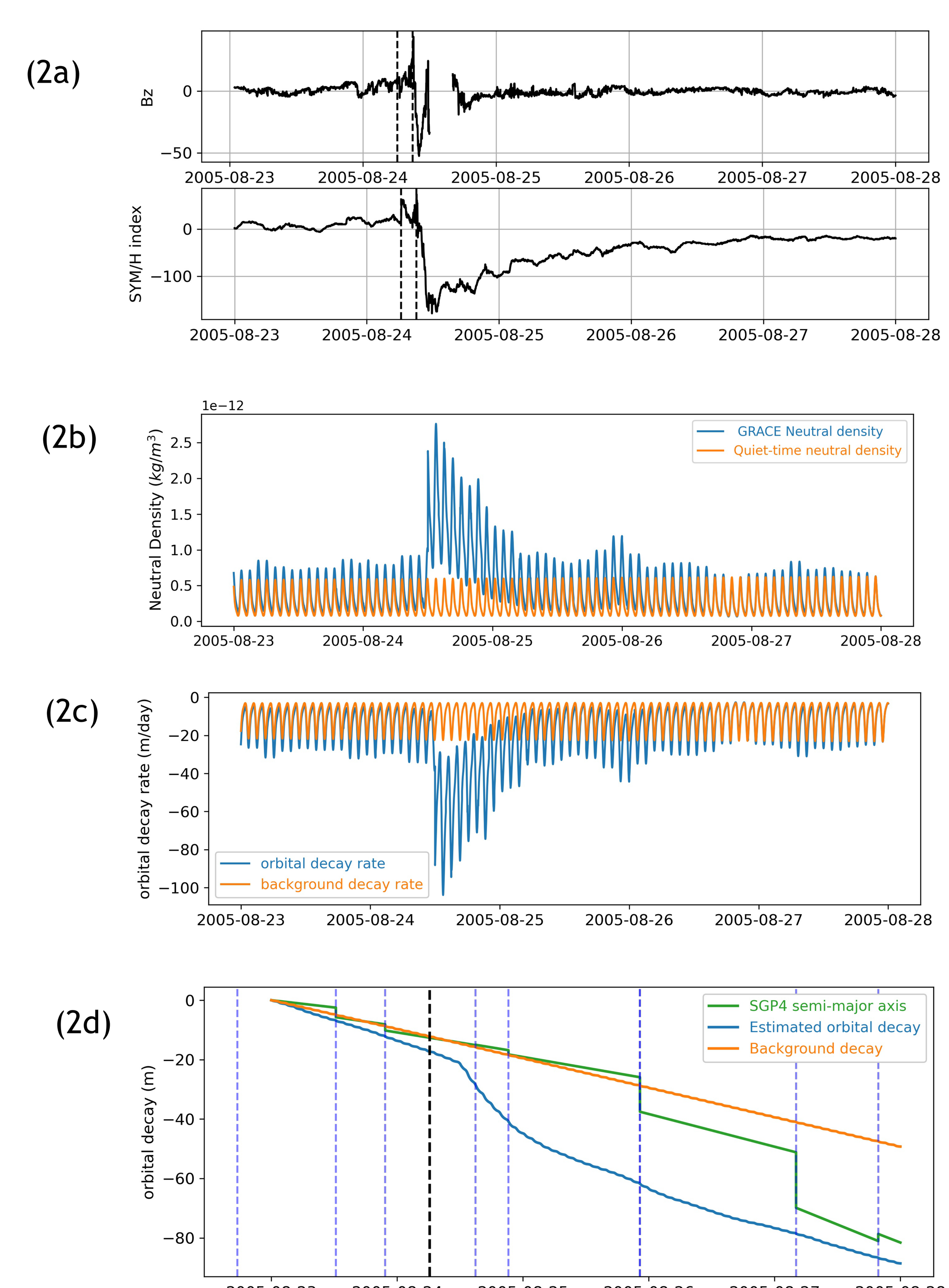


Figure (2a) IMF B_z and SYM-H index for August 23-28, 2005, Vertical dashed lines shows shock impact of CME at August 24 06:30 UT, (1b) Neutral mass density data for GRACE, (1c) storm-time orbital decay rate and (1d) orbital decay compared with SGP4 semi major axis decay. TLE epochs are denoted by purple dashed lines. Black dashed line represents sudden storm commencement.

CONCLUSION

- Results for both satellites show an increased orbital decay rate during storm. This is mainly caused by increased neutral density as well as increased drag co-efficient, which contributes to a larger atmospheric drag force during storm-time.
- Semi-major axis decay from SGP4 shows a linear decay, thus not representing the effect of temporal variation in atmospheric drag. This suggests the requirement of an updated orbit propagation method, which updates the drag term (B^* term in tle), to incorporate the effect of changing drag force in orbit ephemerides.
- Our aim is to modify SGP4 to have an updated B^* term for every orbit. The neutral density, temperature and wind velocity data will be obtained from an updated version of Global Ionosphere Thermosphere Model (GITM).
- The updated GITM uses Auroral Spectrum and High-Latitude Electric field variabilitY (ASHLEY), an empirical model *[(Zhu et al., 2022)]* that introduces the effect of soft electron precipitation and electric field variation at high latitudes. The improvement in neutral density estimation is expected to provide more accurate orbit propagation as well as having a better data-model comparison.

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