

1 **The 2022 Starlink geomagnetic storms: global**
2 **thermospheric response to a high-latitude ionospheric**
3 **driver**

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12 **Key Points:**

- 13 • Ionosphere-thermosphere observations are examined for the 2022 Starlink geomag-
14 netic storms.
- 15 • The thermosphere becomes globally perturbed due to high-latitude magnetosphere-
16 ionosphere forcing.
- 17 • The growth, decay, and latitudinal extent of thermospheric density perturbations
18 are investigated.

Abstract

In this study, we present ionospheric observations of field-aligned currents from AMPERE and the ESA Swarm A satellite, in conjunction with high-resolution thermospheric density measurements from accelerometers on board Swarm C and GRACE-FO, for the 3rd and 4th February 2022 geomagnetic storms that led to the loss of 38 Starlink internet satellites. We study the global storm time response of the thermospheric density enhancements, including their growth, decay, and latitudinal distribution. We find that the thermospheric density enhances globally in response to high-latitude energy input from the magnetosphere-solar wind system and takes at least a full day to recover to pre-storm density levels. We also find that the greatest density perturbations occur at polar latitudes consistent with the magnetosphere-ionosphere dayside cusp, and that there appeared to be a saturation of the thermospheric density during the geomagnetic storm on the 4th. Our results highlight the critical importance of high-latitude ionospheric observations when diagnosing potentially hazardous conditions for low-Earth-orbit satellites.

Plain Language Summary

Upwards of a hundred kilometres altitude lies the boundary between Earth's atmosphere and space, where the density of air exponentially decreases and many satellites constellations orbit. One of these constellations is Starlink, which provides satellite internet to customers on Earth. In February 2022, a pair of geomagnetic storms struck Earth shortly after the launch of 49 Starlink satellites, heating the upper atmosphere and causing its density to drastically increase. The higher air density at the initial staging altitude of Starlink caused fatal drag conditions for 38 of the spacecraft, resulting in their destruction a few days later. This paper examines how the air density of the upper atmosphere changed globally in response to space weather energy being deposited at high latitudes during the Starlink geomagnetic storms of February 2022.

1 Introduction

In February 2022, 38 Starlink internet satellites were destroyed shortly after launch as a result of two back-to-back geomagnetic storms on the 3rd and 4th of that month. These storms carried with them an increase to the amount of Poynting flux entering the high-latitude ionosphere of both hemispheres (e.g. C. Y. Huang et al., 2017), leading to

50 Joule heating and a subsequent perturbation of the thermospheric mass density at low-
51 Earth-orbit (LEO) altitudes (Deng et al., 2009; Wang et al., 2021). Whilst the two storms
52 did ultimately lead to increased thermospheric densities and dangerous orbital drag con-
53 ditions for Starlink, they would not be considered “extreme”, or even “strong”, space
54 weather events, as we demonstrate below. The thermosphere experienced a moderate
55 amount of geomagnetic forcing at high-latitudes, which in turn propagated high densi-
56 ties globally, causing the hazardous conditions at Starlink’s staging altitude of ~ 200 km
57 (Dang et al., 2022; Lin et al., 2022; Laskar et al., 2023). The satellites burned up in Earth’s
58 atmosphere on 7th February, 2022.

59 Not only does increased drag lead to potential launch failures such as that seen in
60 February 2022, but it also affects precise orbit determination, satellite lifespans, and col-
61 lision avoidance (He et al., 2018; Oliveira & Zesta, 2019). Due to LEO altitudes becom-
62 ing increasingly congested, future costly incidents like the Starlink destruction event are
63 likely to become more frequent. Therefore, it is important that we move towards the real-
64 time monitoring and prediction of the thermospheric mass density, and understanding
65 how it responds to space weather forcing.

66 The thermospheric effects of the Starlink storms, like other moderate geomagnetic
67 storms, start at Earth’s high-latitude ionosphere. Field-aligned-currents (FACs) chan-
68 nel solar wind electromagnetic energy into the ionosphere via magnetospheric reconnec-
69 tion events (e.g. the Dungey cycle; Dungey, 1961), which dissipates through Pedersen
70 currents as Joule heating (Foster et al., 1983). As Joule heating is mostly deposited at
71 E-region altitudes where the Pedersen conductivity is highest (Y. Huang et al., 2012),
72 density perturbations at LEO altitudes are mostly generated by the upwelling of neu-
73 tral particles and expansion of the thermosphere due to heating pressure from below (Lu
74 et al., 2016). Travelling atmospheric disturbances (TADs) propagate from high to low
75 latitudes as increased pressure drives an equatorward meridional wind (Pröls & Očko,
76 2000), acting as a vehicle for perturbing globally the thermospheric density (Pröls, 2011).

77 As alluded to, the Starlink storms were not a major space weather event, yet the
78 thermospheric response to those storms were sufficient to cause major damage to space
79 assets. To what extent was the ionosphere perturbed during these storms, and what was
80 the global thermospheric response? To help answer these questions, we present an anal-
81 ysis of ionospheric and thermospheric observations during the February 2022 Starlink

82 geomagnetic storms. As a measure of the space weather input into the atmosphere, we
83 show FAC measurements from the Active Magnetosphere and Planetary Response Ex-
84 periment (AMPERE) and Swarm A satellite. For the thermospheric densities, we em-
85 ploy newly processed high-resolution accelerometer measurements from Swarm C and
86 GRACE-FO. Of particular interest is understanding the global extent of thermospheric
87 perturbations in response to a high-latitude ionospheric driver, investigating the growth
88 and decay of density perturbations, as well as their latitudinal distribution.

89 **2 Data**

90 **2.1 Thermospheric densities from Swarm-C and GRACE-FO**

91 Thermospheric densities in this study were obtained from the Swarm and Grav-
92 ity Recovery And Climate Experiment Follow On (GRACE-FO) missions (Friis-Christensen
93 et al., 2008; Kornfeld et al., 2019). In particular, densities used are derived from accelerom-
94 eters on board Swarm C at an approximate altitude of 450 km and GRACE C at ~ 500 km.
95 Both satellites fly in a near-polar orbit with inclinations of 87.4° and 89° , respectively.

96 The ESA Swarm satellites are the 4th ESA Earth Explorer mission, which was launched
97 in November 2013. They are a constellation of 3 identical satellites flying at different al-
98 titudes. For all three of the Swarm satellites (A, B and C), calibration of the raw accelerom-
99 eter measurements has proven difficult due to unforeseen and/or underestimated non-
100 geophysical perturbations (Siemes et al., 2016). Swarm C proved to contain the least num-
101 ber of disturbances and strongest signal-to-noise ratio of the three satellites, thus mak-
102 ing it the primary focus of neutral density retrieval efforts over the years. Additionally,
103 densities derived from on-board GPS observations, at a low temporal resolution, have
104 helped greatly in higher-resolution accelerometer calibration efforts (Visser & van den
105 IJssel, 2016; van den IJssel et al., 2020). Swarm C accelerometer measurements now pro-
106 vide good thermospheric density estimations at a 10 second temporal resolution, allow-
107 ing for high-latitude density perturbations to be effectively decoupled from those low lat-
108 itudes. We therefore utilise Swarm C accelerometer derived thermospheric densities in
109 this study, as they provide a vast spatio-temporal resolution improvement over GPS den-
110 sities and allow for the effects of high-latitude geomagnetic energy input to be investi-
111 gated more rigorously (Iorfida et al., 2023).

112 GRACE-FO, the successor to the GRACE mission (Tapley et al., 2004) on near-
113 identical hardware, is a twin-satellite mission launched in 2018. Recently, GRACE-FO
114 accelerometer measurements for satellite C of the pair (the other being GRACE D, which
115 unfortunately produced poorer accelerometer data after launch; McCullough et al., 2019)
116 have been released (Siemes et al., 2023), building upon nearly two decades of calibra-
117 tion efforts for the original GRACE, CHALLENGING Mini satellite Payload (CHAMP), and
118 Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellites (Bruinsma
119 et al., 2004; Doornbos, 2012; Mehta et al., 2017; March et al., 2021). Like Swarm C, ther-
120 mospheric densities from GRACE-FO are at a 10 second temporal resolution.

121 **2.2 Field aligned currents from Swarm A and AMPERE**

122 We utilise FAC measurements from the AMPERE campaign (Anderson et al., 2014)
123 and Swarm A satellite. FAC's carry the Poynting flux that is mostly dissipated as Joule
124 heating in the atmosphere (Billett et al., 2023), thus their magnitude and spatial extent
125 act as a key parameter in evaluating high-latitude ionospheric driving of any potential
126 thermospheric density enhancements.

127 Swarm A flies as a satellite pair with Swarm C at the same altitude, separated by
128 1.4° in longitude. FAC estimations are derived from the on-board vector fluxgate mag-
129 netometer (Leger et al., 2009) utilising Ampère's law along with models to remove the
130 terrestrial magnetic field component (Lühr et al., 2015). The Swarm FAC data product
131 has a temporal resolution of 1 second, upon which we apply running mean and Savitsky-
132 Golay filters with 20 second half-window sizes to remove small-scale perturbations and
133 noise.

134 AMPERE produces high-latitude FAC estimations based on magnetometer obser-
135 vations from the Iridium communications constellation. FAC estimates are available on
136 a 1-degree geomagnetic latitude by 1 hour magnetic local time grid, sampled from a spher-
137 ical harmonic fit applied to available magnetometer measurements (after subtraction of
138 Earth's main field) (Waters et al., 2020). AMPERE FAC maps are produced at a nom-
139 inal 10-minute resolution. For the purposes of comparing Swarm A and AMPERE data
140 later in this paper, the AMPERE time intervals shown correspond to average polar pass
141 time of Swarm A, rounded to the nearest 10 minutes.

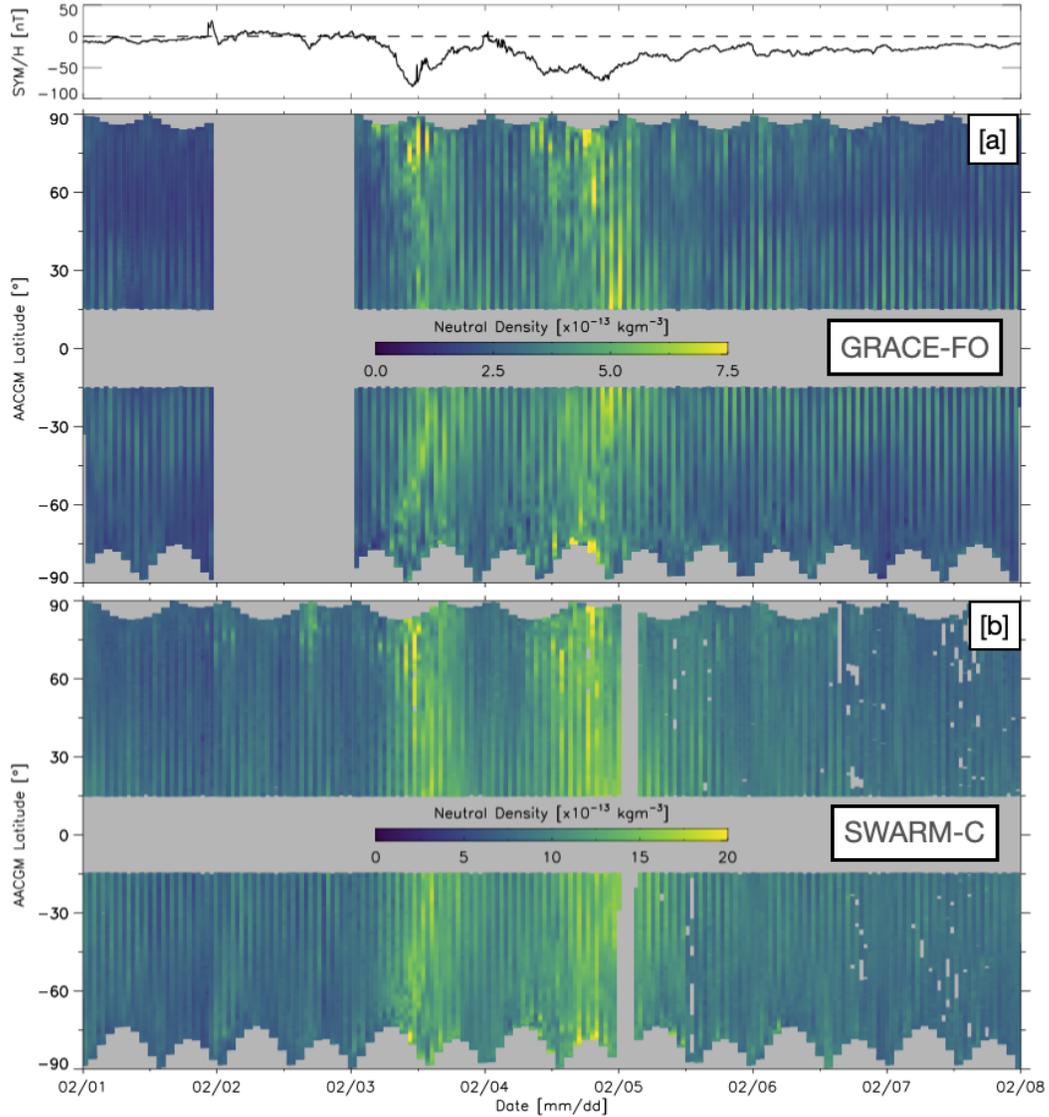


Figure 1. Thermospheric conditions between 1st and 7th February 2022. [Top] 1-minute SYM-H index, [a] Thermospheric neutral density as a function of AACGM latitude and time from GRACE-FO, [b] Densities from Swarm C.

142 3 Results and Discussion

143 3.1 Thermospheric density response and decay

144 Figure 1 presents an overview of the days surrounding the Starlink satellite launch
 145 on 3rd February, 2022. The top panel shows the 1-minute geomagnetic SYM-H index,
 146 obtained from NASA's OMNIWeb service, whilst panels [a] and [b] show the thermospheric
 147 neutral densities measured by GRACE-FO and Swarm C, respectively. The neutral den-

148 sities are shown in terms of Altitude Adjusted Corrected Geomagnetic (AACGM; Shep-
149 herd, 2014) latitude versus time, with periodic gaps near $\pm 90^\circ$ illustrating the offset of
150 the geomagnetic pole from that of the geographic in both hemispheres. As both GRACE-
151 FO and Swarm C have near-polar orbits in geographic coordinates, coverage above $\pm 80^\circ$
152 AACGM latitude is poorer in the southern hemisphere compared to north. As AACGM
153 coordinates are not defined for equatorial latitudes, latitudes between -15° to $+15^\circ$ are
154 not considered. Note that each “half orbit” is shown sequentially, giving the appearance
155 of periodic increases and decreases of the neutral density as the satellite crosses the day-
156 side (higher density), and then the nightside (lower density). GRACE-FO data was un-
157 available on 2nd February, 2022.

158 The SYM-H index shown in Figure 1 displays a distinct negative excursion to \sim -
159 80 nT on 3rd February 2022, the day of the Starlink launch. Storm magnitude classifi-
160 cations vary greatly within the literature, however, a storm of SYM-H magnitude as seen
161 during this event would be generally considered “weak” or “moderate” (Hutchinson et
162 al., 2011; Richardson & Cane, 2012; Long et al., 2022). Concurrent with the 3rd Febru-
163 ary storm are global scale enhancements of the thermospheric neutral density, captured
164 by both GRACE-FO and Swarm C at altitudes of ~ 500 km and ~ 460 km, respectively.
165 Note that the colour scales on Figure 1[a] and [b] are different, owing to the normal ex-
166 ponential drop of neutral density with increasing altitude in the thermosphere. The peak
167 neutral density, seen by both GRACE-FO and Swarm C, is at around 80° AACGM lat-
168 itude in the northern hemisphere. We attribute this high latitude density peak to ge-
169 omagnetic energy input from the magnetosphere in the form of Joule heating into the
170 ionospheric cusp region (Lühr et al., 2004; Knipp et al., 2011; Billett et al., 2021).

171 A second geomagnetic storm, longer lasting than the one on 3rd February but of
172 a similar SYM-H magnitude, occurred on 4th February 2022, one day after the Starlink
173 launch. There is another global response of the thermospheric neutral density on the 4th,
174 including an equatorward motion of density enhancements from high northern and south-
175 ern latitudes over the course of the day, most apparent in the GRACE-FO measurements.
176 This motion is consistent with TAD propagation, and modelling of the same event (Lin
177 et al., 2022; Laskar et al., 2023).

178 To evaluate the growth and decay of the thermospheric neutral density in response
179 to the geomagnetic storms of the 3rd and 4th February, 2022, Figure 2 shows the hourly

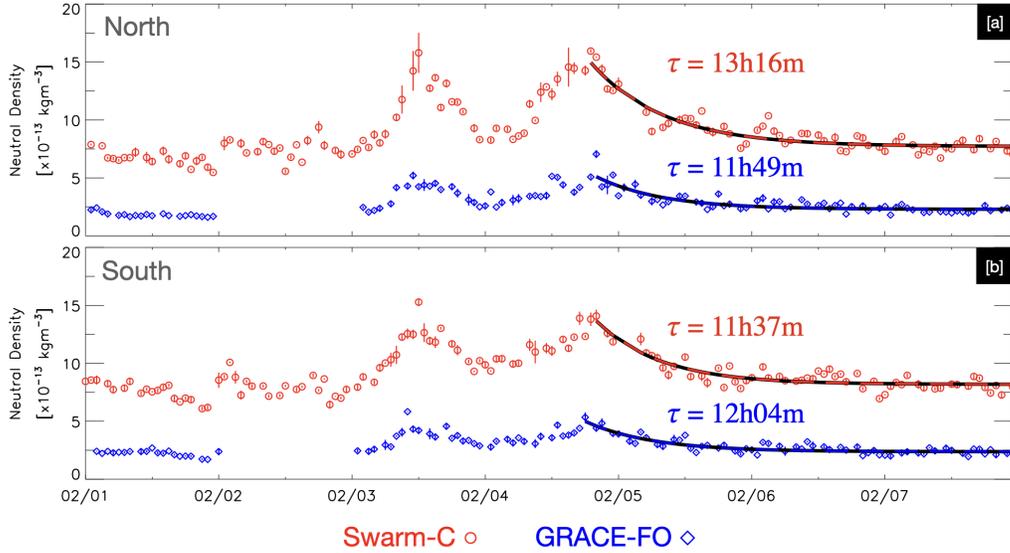


Figure 2. Mean thermospheric neutral densities between 60° and 70° AACGM latitude from 1st and 7th February 2022, measured by GRACE-FO and Swarm C. [a] Northern hemisphere, [b] Southern hemisphere. Exponential decay curves are fitted from the second peak of each time series onwards, with e-folding times for each shown.

180 averaged densities from GRACE-FO and Swarm C between 60° and 70° AACGM lat-
 181 itude, in the northern [a] and southern [b] hemispheres, respectively. The latitude range
 182 was chosen to ensure similar satellite coverage in both hemispheres (owing to the poorer
 183 polar coverage in the south), whilst being at a latitude high enough to capture magne-
 184 tospheric energy inputs due to the geomagnetic storms (i.e. the auroral zone) reason-
 185 ably soon after they occur. The curves from 4th February onwards are exponential decay
 186 least-square fits in the form $\rho(t) = ae^{-t/\tau} + b$, where $\rho(t)$ is the neutral density as
 187 a function of time, a and b are fit constants, and τ is the e-folding time. τ is strictly the
 188 time taken for the thermospheric density to decrease by a factor of $1/e$, which we use
 189 as representative of the time required for the thermosphere to “recover” after the geo-
 190 magnetic storm on 4th February. The root-mean-square errors (RMSE) of the exponen-
 191 tial fits, as a percentage of the mean of the data that was fitted, are 7.6%/6.7% for Swarm
 192 (north and south, respectively), and 15.9%/11.8% for GRACE-FO.

193 Both GRACE-FO and Swarm C measured two distinct neutral density peaks in
 194 the auroral zones of both hemispheres (Figure 2a and b), in response to the geomagnetic
 195 storms on the 3rd and 4th February, 2022. These time series, averaged over the latitude

196 range 60-70°, are broadly similar to the global orbit averaged time series shown by Lin
 197 et al. (2022) for Swarm A, as well as the MAGE, TIEGCM and DTM model outputs.
 198 The storm-time density in this latitude range was 1.9% and 2.8% higher in the south-
 199 ern hemisphere compared to the north at GACE-FO and Swarm C altitudes, respectively.
 200 This hemispheric difference is rather small considering that the southern hemisphere is
 201 in local summer, which should result in a significantly larger overall density than the win-
 202 ter (northern) hemisphere (Ercha et al., 2012). It has previously been seen that there
 203 is a northern hemisphere preference for increased magnetospheric energy input when com-
 204 pared to the south (Pakhotin et al., 2021), which would result in a density asymmetry
 205 due to Joule heating.

206 Other hemispheric asymmetries in Figure 2 are present. For example, the density
 207 trough around midnight on the 4th of February between the two storm peaks is deeper
 208 in the northern hemisphere compared to the south for the same spacecraft. This would
 209 imply a quicker decay time for the enhanced neutral density to return to background lev-
 210 els in the northern hemisphere after the storm on 3rd February. τ values calculated from
 211 the peak of the 2nd storm onwards, however, do not indicate a faster northern hemisphere
 212 recovery for the second storm. τ varies between spacecrafts and hemispheres, ranging
 213 from 11h37m to 13h16m, but the decay time from Swarm C in the northern hemisphere
 214 is significantly longer than the rest, which vary by around 30 minutes. τ for for Swarm
 215 C in the north is 1 hour 12 minutes longer than the next closest τ , which could mean that
 216 the density perturbation in the northern hemisphere around 460 km is larger than that
 217 in other regions, that the thermosphere there is more “sluggish” in returning to pre-storm
 218 levels, or a combination of both conditions. As SYM-H takes several days to return to
 219 values near zero after the storm on 4th February (Figure 1), it is also possible there is
 220 persistent Joule heating that lingers and causes the neutral density to not fully return
 221 to quiet-time levels (Zhou et al., 2007). We note that because the RMSE of the expo-
 222 nential fit for Swarm in the northern hemisphere was 7.6% (approximately 1 hour error
 223 in τ), its longer e-folding time may be within error tolerances of the others. The appar-
 224 ent quick thermospheric decay time after the first storm, on 3rd February, may be due
 225 to enhanced nitric oxide cooling associated with coronal mass ejection (CME) driven storms
 226 (Knipp et al., 2017; Licata et al., 2022), although an exact τ cannot be determined due
 227 to the onset of the second storm. Overall decay times presented here are consistent with

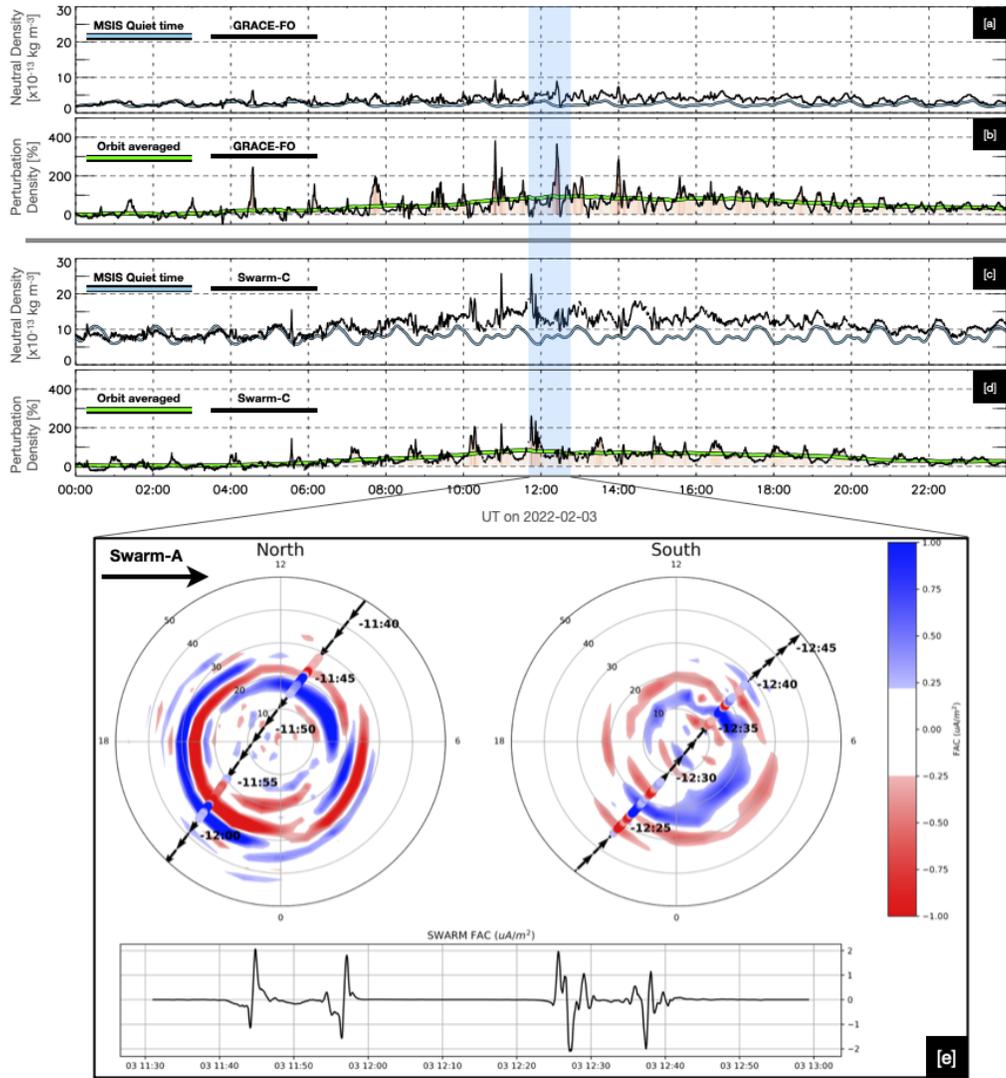


Figure 3. Thermosphere/ionosphere conditions on 3rd February 2022. [a] and [c]: Time series of measured thermospheric densities from GRACE-FO [a] and Swarm C [c], with MSIS quiet time estimations. [b] and [d]: Perturbation thermospheric densities from GRACE-FO [b] and Swarm C [d], with orbit averaged values underlain. [e] AMPERE and Swarm A FAC measurements from within the shaded region.

228 those presented in the statistical study by Zesta and Oliveira (2019), and likely vary some-
 229 what with local time (e.g. Weimer et al., 2023).

3.2 Disturbance thermospheric densities and ionospheric drivers

We now discuss the high-latitude ionospheric conditions responsible for driving the globally enhanced thermospheric densities on the 3rd and 4th February 2022. Figure 3a and c shows neutral density measurements from GRACE-FO and Swarm C on 3rd February, 2022, accompanied by estimations of the “quiet time” density from the Naval Research Laboratory Mass Spectrometer Incoherent Scatter radar model (NRLMSIS 2.0, shortened to “MSIS” in this study; Emmert et al., 2021). $A_p = 3$ as MSIS input was chosen to represent “quiet” geomagnetic conditions for the purpose of this study (Joselyn, 1989), which was found to closely resemble the GRACE-FO and Swarm C measurements on the two days prior to the 3rd of February storm. Figure 3b and d show perturbation neutral densities derived by subtracting the quiet time MSIS estimations from the satellite measurements. Orbit averaged perturbation densities are additionally shown here, calculated using a running mean window of size equal to the respective satellites orbital period. Figure 3e shows global AMPERE and local Swarm A FAC measurements during the shaded interval. Overlain black arrows are Swarm A’s trajectory over the northern and southern hemisphere high-latitude regions, extending to 50° colatitude (40° AACGM latitude). Swarm A data is shown both as coloured circles over the AMPERE data, as well as a time series. Blue (positive) FAC values are downward (into) in the northern hemisphere and upward (out of) in the south, and vice versa for red.

The negative excursion of SYM-H signifying the start of the storm on 3rd February (Figure 1) begins at $\sim 05:00$ UT. It is from approximately then that the neutral density measurements from GRACE-FO and Swarm C begin to deviate from MSIS estimations (Figure 3a and c). Other than the deviation from quiet time baselines, MSIS appears to capture latitudinal and local time variability of the satellite densities well. The deviation is clearer in the perturbation densities (Figure 3b and d), showing that those at both ~ 460 km and ~ 500 km altitude become enhanced at approximately the same time. The perturbation densities also reveal that both GRACE-FO and Swarm C measure peaks at around the same time, within the highlighted region at 12:00UT, giving a time lag of ~ 7 hours between storm onset and peak density perturbation. The maximum single-point perturbation density measurement and orbit averaged perturbation density was 380%/96% for GRACE-FO, respectively, and 260%/84% for Swarm C. We note that although the orbit averaged density perturbation presented here is similar to that determined by other studies for the Starlink storms (Lin et al., 2022; Dang et al., 2022), the

263 moment-to-moment densities at both GRACE-FO and Swarm C altitudes often greatly
264 exceed the average, especially at high latitudes.

265 AMPERE and Swarm A FACs are shown in Figure 3e for the shaded interval in
266 panels a-d, roughly coinciding with the time of peak perturbation density. AMPERE and
267 Swarm A are in good agreement with each other. The northern hemisphere FAC pat-
268 tern extended further equatorward than in the south and contained higher current mag-
269 nitudes (which would result in more Joule heating). However, both hemispheres display
270 FACs indicative of active magnetospheric forcing. The northern hemisphere FAC is more
271 akin to a “classical” FAC picture than the south, with clearly structured R1 and R2 cur-
272 rents on both the dawn and dusk sides (Iijima & Potemra, 1978).

273 Figure 4a-d shows thermospheric conditions for 4th February 2022, one day after
274 the Starlink launch and the day of the second geomagnetic storm. The SYM-H onset of
275 this storm was at approximately 01:00 UT, with a peak negative excursion reached at
276 \sim 21:00 UT (Figure 1). The peak perturbation neutral density observed by both GRACE-
277 FO and Swarm C occurred around 19:00 UT, an 18 hour lag from storm onset. This much
278 longer lag time, compared to the 3rd, is probably due to the long \sim 20 hour main phase
279 indicated by the SYM-H index. It is interesting that the peak perturbation density on
280 the 4th occurred 1-2 hours before the peak SHM-H negative excursion, as it implies there
281 is perhaps a thermospheric density “saturation” point that is based on the duration of
282 the storm main phase, and/or the magnitude of the storm itself. The peak single-point
283 perturbation density measurement and orbit averaged perturbation density was higher
284 on the 4th compared to the 3rd, 476%/125% respectively for GRACE-FO. Swarm C mea-
285 sured several very large density perturbations over a 5-minute period at 18:50 UT which
286 were not flagged as anomalous in the data quality flags, resulting in a maximum single-
287 point perturbation density measurement of 510%. We treat this as anomalous as the max-
288 ima during the preceding and proceeding peaks were under 200%, and because the ther-
289 mospheric density is highly unlikely to vary by so much so quickly. The peak orbit-averaged
290 perturbation density measured by Swarm C was 107% (excluding anomalous points), higher
291 than that seen on the 3rd of February.

292 The orbit averaged densities from GRACE-FO and Swarm C were considerably higher
293 on the 4th of February compared to the 3rd, by 29% and 23%, respectively. We attribute
294 this difference to the global extent of density enhancements that each storm produced.

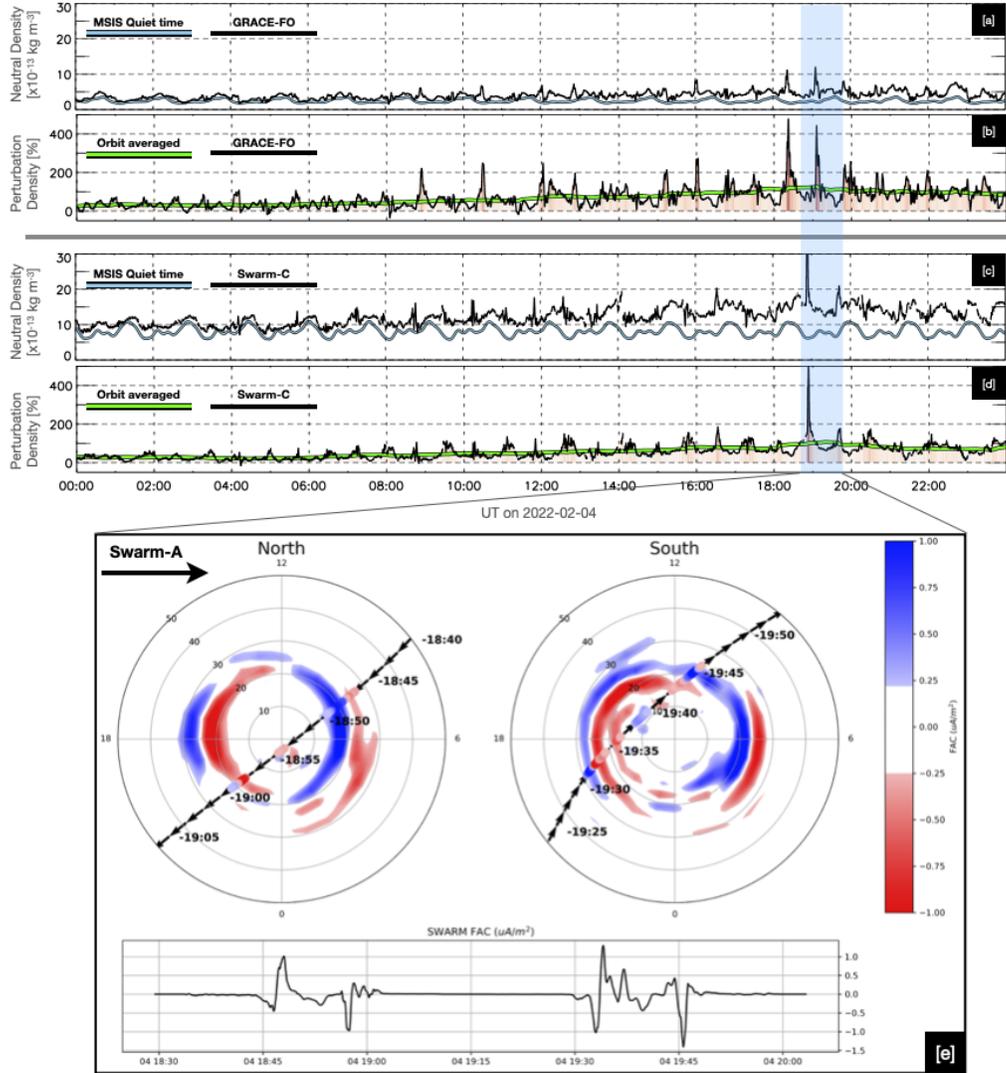


Figure 4. Same format as Figure 3, but for 4th February 2022.

295 Figure 1a and b shows that the storm on the 4th resulted in density perturbations prop-
 296 agating to low latitudes, whilst enhancements on the 3rd were mostly at northern hemi-
 297 sphere high latitudes. The density asymmetry seen on the 3rd is not seen on the 4th,
 298 which may be related to the aforementioned FAC asymmetry (Figure 3e). On the 4th,
 299 the northern and southern hemisphere FACs observed by AMPERE and Swarm A are
 300 more symmetric (Figure 4e), which would result in more symmetric Joule heating, and
 301 thus a more symmetric distribution of density enhancements and TAD propagation. The
 302 latter causes an “intersection” of TADs at low latitudes, driving significant density en-
 303 hancements there (e.g. those seen on the 4th February in Figure 1) (Pham et al., 2022).

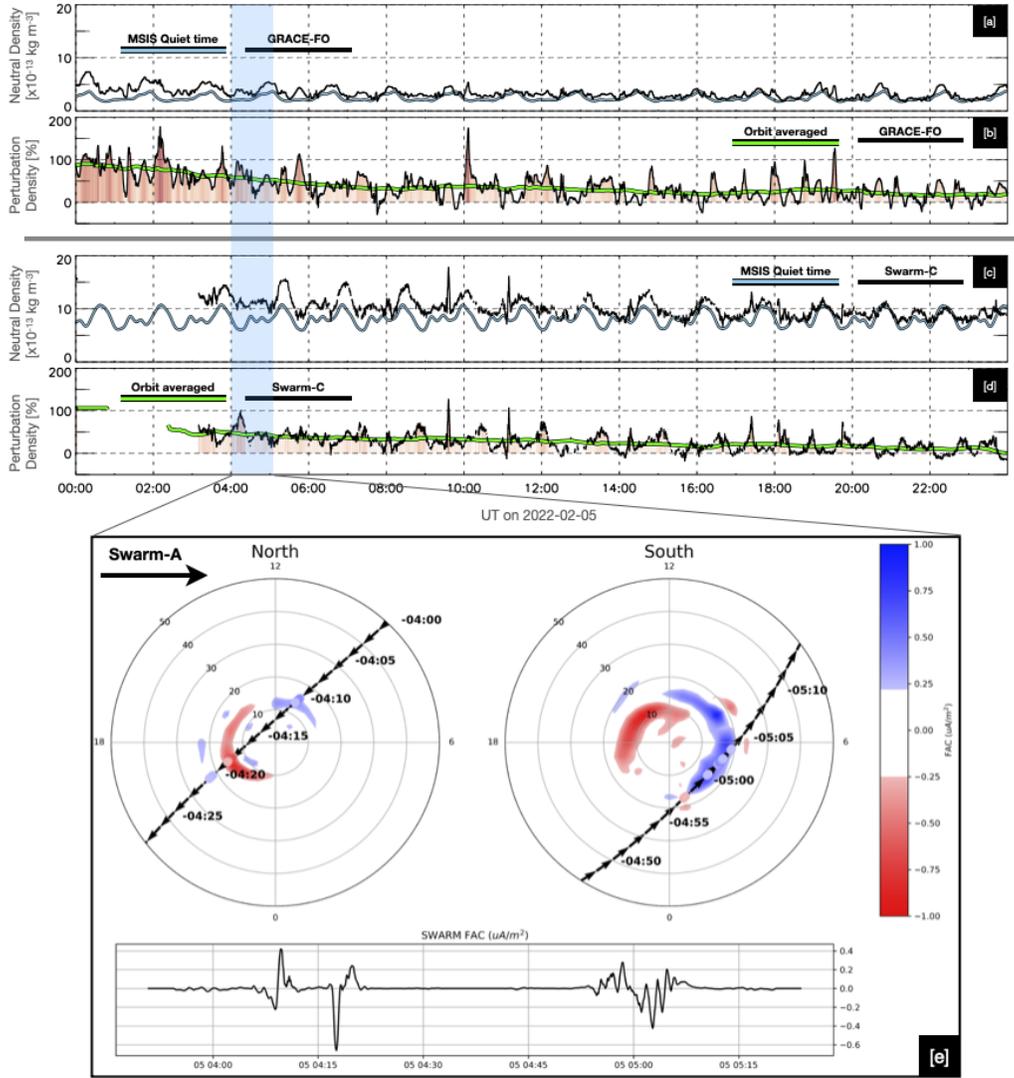


Figure 5. Same format as Figure 3, but for 5th February 2022.

304 Thus, the asymmetric FACs on the 3rd would produce asymmetric TAD propagation,
 305 in agreement with recent modelling work (Zhu et al., 2023; Hong et al., 2023).

306 Next, we demonstrate that the thermospheric enhancements were significantly longer
 307 lived than the storm itself. Figure 5 is in the same format as Figures 3 and 4, but show-
 308 ing the 5th of February 2022 (the day after the second storm, two days after the Star-
 309 link launch). There were no additional storms on this day according to the SYM-H in-
 310 dex (Figure 1) and the densities observed by GRACE-FO and Swarm C gradually de-
 311 creased throughout the day, eventually returning close to the MSIS quiet-time base-
 312 AMPERE and Swarm A FAC's are shown for the highlighted times around 04:30 UT (Fig-

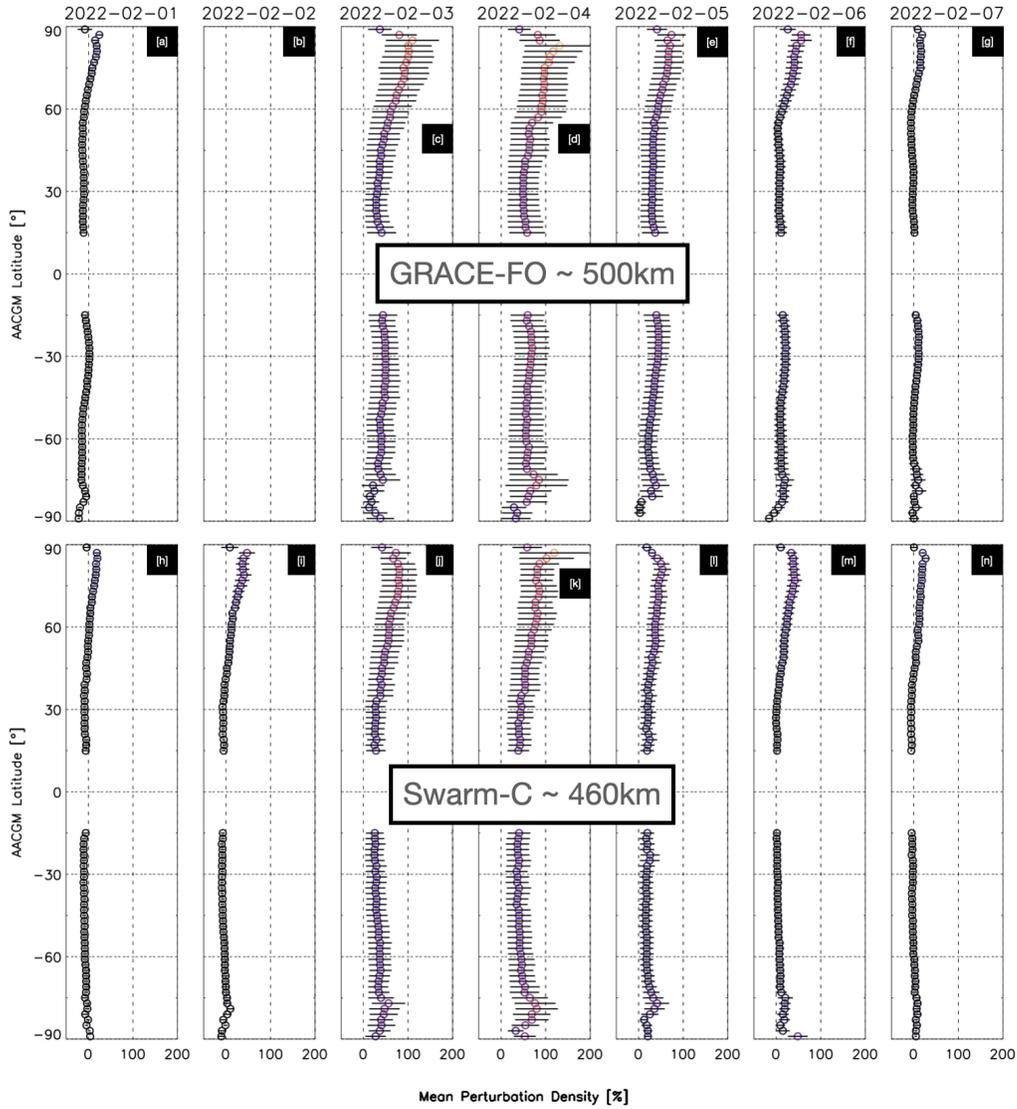


Figure 6. Latitude profiles of the mean thermospheric density from GRACE-FO [a-g] and Swarm C [h-n], for 1st - 7th February 2022.

313 ure 5e), showing that the FAC equatorward extent and magnitude were drastically re-
 314 duced compared to the previous two storm days. Figure 5 illustrates that the thermo-
 315 sphere after the storms took at least a full day to return to near-quiet-time density lev-
 316 els (with e-folding times given in Figure 2), whilst the ionospheric driving conditions de-
 317 cayed much faster. FAC reconfiguration timescales after changes in solar wind driving,
 318 and in turn Joule heating reconfiguration times, are typically on the order of 10-150 mins
 319 (Anderson et al., 2018; Coxon et al., 2019; Billett et al., 2022).

320 Finally, we investigated the latitudinal dependence of the perturbation thermospheric
321 density by creating daily mean profiles versus latitude, shown in Figure 6 from 1st to 7th
322 February 2022. The 7th of February is the date on which the failed Starlink satellites
323 burned up on re-entry.

324 The largest perturbation densities were seen on storm days (Figure 6c, d, j, k), with
325 larger perturbations seen by GRACE-FO compared to Swarm C (500 km/460 km aver-
326 age altitude, respectively). GRACE-FO measured maximum mean perturbations of 110%
327 and 131% on the 3rd and 4th respectively, compared to Swarm C measurements of 80%
328 and 86%. Maximums from both satellites were in the northern hemisphere, at polar cap
329 latitudes between 75° and 85° . These latitudes are considerably higher than typical au-
330 roral latitudes of $\sim 65^\circ$ - 70° , implying that the peak magnetospheric energy input into
331 atmosphere for these storms is occurring on open magnetic field lines, or close to the open-
332 closed field line boundary. This is a similar result to those presented by R. Liu et al. (2010),
333 C. Y. Huang et al. (2014), Shi et al. (2017), and Wang et al. (2021), who all saw large
334 geomagnetic storm-associated thermospheric density enhancements occurring well within
335 the polar cap. These enhancements have been attributed to Joule heating in the region
336 of enhanced cusp FACs and are likely related to the development of the “cusp density
337 anomaly” (Lühr et al., 2004). The latitudinal width of density enhancements were also
338 smaller in the southern hemisphere compared to north, which is consistent with the sta-
339 tistical distribution of the cusp density anomaly in both hemispheres (H. Liu et al., 2005).

340 It is noted there were also discernible high latitude perturbations on average dur-
341 ing the two days before the first storm (Figure 6a, b, h, i), particularly in the northern
342 hemisphere, even though the geomagnetic activity levels were low (Figure 1). Significant
343 perturbation densities on these days, although much smaller than those on storm days,
344 implies that MSIS underestimates the high-latitude thermosphere to some degree when
345 using $A_p = 3$ as quiet time input. Alternatively, there may also be lingering thermospheric
346 density enhancements on the 1st and 2nd February due to a minor geomagnetic storm
347 that occurred at the end of January (Berger et al., 2023). Therefore, perturbation den-
348 sities presented in this study are likely to be overestimations.

4 Summary

We have presented an analysis of the ionosphere-thermosphere conditions which lead to the loss of Starlink internet satellites in February 2022. Discrete geomagnetic storms on the 3rd and 4th February drove increases of the thermospheric mass density, increasing drag on the satellites and leading them to de-orbit on the 7th.

Utilising newly processed high-resolution thermospheric density measurements from Swarm C and GRACE-FO, we have gained new insights into the global extent of density enhancements due to high-latitude ionospheric driving (captured by AMPERE and Swarm A FAC measurements). In particular:

- Thermospheric densities become enhanced globally, but are largest in the high-latitude polar regions above 80° AACGM latitude. The latitudinal distribution of the density perturbations is consistent with magnetospheric energy input into the cusp.
- Density perturbations between the northern and southern hemispheres were more symmetric on the 4th compared to the 3rd. This is consistent with the FAC data from AMPERE, which likewise exhibits stronger hemispherical symmetry on the 4th compared to the 3rd of February.
- Thermospheric density e-folding decay timescales in the auroral zones of both hemispheres were approximately 12 hours, except for Swarm C in the northern hemisphere, which was around 13 hours. The magnitude and extent of FACs reduced much quicker.
- The perturbation thermospheric density on the 4th appears to saturate, with its peak occurring 1-2 hours before the maximum excursion of SYM-H. This may be due to the very long main phase of the 4th of February storm, which lasted around 20 hours.

This study emphasises the importance of capturing high-latitude ionospheric conditions when considering the impact of geomagnetic storms on the thermosphere, which can have dire consequences for LEO assets. These thermospheric storm effects are global in their extent and complex in their growth and decay, whilst their drivers are confined to high latitudes. There is additionally a complex thermospheric interplay between hemispheres, as ionospheric conditions in each can be highly asymmetric. For future anal-

380 ysis and potential real-time monitoring to support LEO satellite launches, capturing the
 381 high-latitude ionosphere is imperative.

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 389 downloaded at <http://ampere.jhuapl.edu/>. The NRLMSIS 2.0 model Fortran code
 390 was obtained from <https://map.nrl.navy.mil/map/pub/nrl/NRLMSIS/NRLMSIS2.0/>.

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