

Comparative Accuracies of Models for Drag Prediction During Geomagnetically Disturbed Periods: A First Principles Model versus Empirical Models

By R. L. Walterscheid^{1,3}, M. W. Chen¹, C.- C. Chao², S. Gegenheimer^{2,†}, J. Cabrera-Guzman^{1,2},
and J. McVey²

1. Space Science Applications Laboratory, The Aerospace Corporation, Los Angeles, CA 90009

2. Astrodynamics Department, The Aerospace Corporation, Los Angeles, CA 90009

3. Physical Sciences Department, Embry-Riddle Aeronautical University, Daytona Beach, FL,
32114

† Present affiliation: Binti, Inc., San Francisco, CA

Abstract

We examine the accuracy of density prediction by the first principles model Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) developed by the National Center for Atmospheric Research and compare it to the accuracy of three empirical models: Jacchia 71, the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000 (NRLMSIS), Jacchia 1971 and Jacchia-Bowman 2008. Comparisons are made for three large storms: the October 2003 storm, the March 2013 storm, and the March 2015 storm. To evaluate the accuracy of these models we use tracking data for nine space objects in low Earth orbit. Additionally, we evaluate the accuracy of the TIEGCM and NRLMSIS with data from high precision accelerometers on the Challenging Minisatellite Payload (CHAMP) and Gravity field and Circulation Explorer (GOCE) satellites. The goal is to assess the use of a first principles model as a potential tool for forecasting satellite drag during large magnetic storms. For the storms considered, we found the TIEGCM, JB2008 and NRLMSIS models to be substantially more accurate than the Jacchia 71 model. The accuracies of the TIEGCM and JB2008 models were similar, but overall, the TIEGCM was more accurate. We found smaller differences for TIEGCM versus CHAMP than for NRLMIS for the Halloween Storm, and smaller differences than results published for JB2008 and the assimilative model HASDM. The empirical models are at present more practical for operational purposes, but the TIEGCM, developed as a research model, with a greater focus on operational use offers the potential for improved utility during stressing conditions.

Plain Language Summary

We examined the accuracy of density prediction by the physics-based Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) developed by the National Center for Atmospheric Research and compare it to the accuracy of three data-based models: Jacchia 71, the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000 (NRLMSIS), Jacchia 1971 and Jacchia-Bowman 2008 (JB2008). Comparisons are made for three large magnetic storms. To evaluate the accuracy of these models we use tracking data for nine space objects in low earth orbit. Additionally, we evaluate the accuracy of the TIEGCM and NRLMSIS with data from the Challenging Minisatellite Payload and Gravity field and Circulation Explorer satellites. The goal is to assess the use of a physics-based model as a potential tool for forecasting satellite drag during large magnetic storms. For the three storms considered, we found the TIEGCM, JB2008 and NLMSIS accuracies to be substantially better than for Jacchia 71. The TIEGCM and JB2008 models were similar, but overall the TIEGCM was slightly more accurate. The empirical models are at present more practical operationally, but the TIEGCM was developed as a research model and with a greater focus on operational use offers the potential for improved utility during stressing conditions.

Key Points:

- The accuracy of TIEGCM density prediction during storms is compared to empirical models using tracking data for objects in low earth orbit.
- TIEGCM accuracy is substantially better than the Jacchia 71 model during three large magnetic storms.
- The accuracies of the TIEGCM and JB2008 models are similar, but overall, the TIEGCM was more accurate.

1. Introduction

The foremost operational use of density models is for the calculation of atmospheric drag on satellites. Drag (acceleration) is related to density as follows:

$$a = \rho C_D (A/m) (V^2/2) \quad (1)$$

where a is acceleration, ρ is air mass density, C_D is the drag coefficient, V is the velocity relative to air, A is the satellite cross-sectional area normal to the velocity and m is satellite mass.

During large geomagnetic storms, the atmospheric density disturbance can cause large tracking errors. For example, the large storm of March 1989 (Ap index exceeding 150, at peak) caused a loss of track for approximately 1400 satellites (Gorney et. al., 1993).

Empirical models have done a remarkable job of representing very large solar cycle, diurnal and transient (storm) variations of an order of magnitude or greater and reducing the unmodeled variation to ~ 10 -15% (Marcos, 1990; Marcos et al., 1998, Bowman et al., 2008). However, empirical neutral density models are subject to irreducible errors that arise because of the statistical nature of the models (e.g., Zesta and Huang, 2016). It would require a very large list of parameters to characterize the system fully, and no realizable data base would support partitioning (binning) the data among all but a small subset of the parameters. For very large storms, this is compounded by the fact that parameters characterizing the storms may be near, or exceed, the bounds of the parameter space of the underlying data base, and thus the density predictions may lack sufficient statistical support.

An improvement on a purely statistical model is the use of an empirical model modified with the use of assimilated real time tracking data. This has led to a significant improvement in density

specification (Storz et al., 2005). At present, the real time output of this High Accuracy Satellite Drag Model (HASDM) is not publically available.

While the potential for first principles models is greater, the present competitiveness of a first principles models (which are primarily research tools not focused on density prediction) relative to empirical models (which are developed for operational purposes, as well as research) must be shown. In this article we compare the accuracy of the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), a widely used first-principles model of the thermosphere, to three widely used empirical models: Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000, Jacchia 1971 and Jacchia-Bowman 2008. Comparisons are made for three large storms: the October 2003 storm, the March 2013 storm, and the March 2015 storm. To evaluate the accuracy of these models we use tracking data for nine space objects (three for each storm). Additionally, we evaluate the accuracy of the TIEGCM and NRLMSIS with data from high precision accelerometers on the Challenging Minisatellite Payload (CHAMP) and Gravity field and Ocean Circulation Explorer (GOCE) satellites.

We address the accuracy of the TIEGCM under conditions when the utility of first principles model is likely to be greatest: under conditons when large and rapidly evolving changes in the upper atmosphere are caused by large magnetic storms. We do not address the relative accuracies of the TIEGCM and empirical models under more typical conditions. Furthermore, the limitations of the TIEGCM restrict the applicability of the results to altitudes below 500-700 km, depending on solar activity.

In the following sections we describe the density models (first principles and empirical), the drag calculations based on tracking data, and the *in situ* satellite density data; present the model to data comparisons; discuss the results; and give the study conclusions.

2. Model Descriptions

2.1. Empirical models

2.1.1. Naval Research Laboratory Mass Spectrometer Incoherent Scatter Extended 2000 (NRLMSIS)

The NRLMSIS model is an empirical model based originally on mass spectrometer and incoherent scatter radar data, and updated with drag data (Picone et al., 2002). The “Extended” version provides density, temperature and composition from the Earth’s surface to 1000 km altitude as a function of latitude, longitude and altitude, time of day and time of year. The model inputs parameterizing heating of the thermosphere are the solar index F10.7 and the daily average of the three-hourly geomagnetic index ap. The former is the 10.7 cm solar radio flux which is found to be highly correlated with the flux of solar extreme ultraviolet (EUV) radiation (Hinteregger, 1980). The absorption of EUV by thermospheric constituents through ionization and photodissociation is the primary source of heating of the thermosphere. The ap index is based on the K index derived from ground-based magnetometers and is a measure of the currents generated in the ionosphere. The K index is the maximum fluctuation of horizontal magnetic field components observed on a magnetometer during a three-hour interval (Bartles, 1939). The NRLMSIS model is based on a fit to data using spherical harmonics (geographic latitude and longitude), Fourier series (time of day, time of year) and a vertical static diffusion representation of vertical structure. Fitting coefficients can depend on F10.7 and ap (Ap).

2.1.2. Jacchia 1971

The Jacchia 1971 model is one of the early thermospheric models that is widely used. It is based on satellite drag data (Jacchia, 1971). The model employs a table look-up scheme. It provides density and temperature as a function of altitude, latitude, longitude, local time, time of day and time of year. Auxiliary tables are provided to evaluate geomagnetic, semi-annual, and seasonal-latitudinal effects. The solar flux parameter is the F10.7 index, and the geomagnetic parameter is

the Kp index, which like ap is based on the K index (Bartels, 1939). The altitude domain is from 90 km to 2500 km. The vertical profile is based on static diffusion. A model in this family (Jacchia, 1970) is used as the background model for HASD. This model uses assimilated tracking data from a number of well characterized tracked objects to improve model accuracy (Storz, 2005).

2.1.2. Jacchia Bowman 2008 (JB2008)

The JB2008 model (Bowman et al., 2008) is structurally similar to Jacchia 1971 and is based on Jacchia's static diffusion equations. It adds three new solar indices, S10, M10 and Y10, in addition to F10.7 (Chao and Hoots, 2018). These indices are derived from solar irradiance measurements and scaled to F10.7 (Licata, 2020). The JB2008 model also includes exospheric temperature responses to the *Dst* index.

2.2. The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM)

The National Center for Atmospheric Research TIEGCM is a comprehensive, first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system (Roble et al., 1988; Richmond et al., 1992). The model solves the three-dimensional momentum, energy and continuity equations for compressible quasi-static motion on the sphere. The vertical coordinate is a log pressure coordinate. The model solves for atomic oxygen, molecular oxygen and nitrogen. It also solves for a number of ionic species. The lower boundary is located near 97 km and the upper boundary is located from ~ 500 km to 700 km depending on solar activity. Model heat and momentum inputs include solar EUV heating based on a F10.7 based parameterized spectrum. Joule heating, ion drag and particle heating are based on schemes that depend on indices of geomagnetic activity. Tides coming up from below are specified at the lower boundary. Model output includes geopotential height of log-pressure surfaces, composition, temperature and winds. Density as a function of altitude is derived from model output using pressure, temperature and

geopotential. We used the NCAR TIEGCM version 1.95 for the October 2003 storm and the version 2.0 for the March 2013 and March 2015 storms with 2.5° resolution in both latitude and longitude. We used the more recent NCAR TIEGCM version for the latter events because version 2.0 was available when we had research funding available to carry out those simulations. Version 2.0 includes helium that can be a significant contribution to mass density about 500 km especially near solar minimum while version 1.95 does not. The storm events that we simulate are not during solar minimum. The Heelis et. (1982) electric field model was used to calculate the high latitude electric potentials. The daily F10.7 solar, the 81-day centered average F10.7A, and the 3-hour Kp geomagnetic indices were used as input.

3. Orbital Drag Calculations:

Nine inactive decaying satellites with altitudes between 290 and 430 km were selected from the space catalog and their Two Line Element (TLE) data were processed for in-track, cross track and radial error determinations. Each satellite or object has a North America Aerospace Defence Command (NORAD) identification number (ID) and its TLE data was obtained from SpaceTrack.org. Three magnetic storm periods were examined. Three different sets of three decaying satellites were used, one set for each storm. Position errors after fitting a span of 5 to 6 days of TLE data for the each event were determined.

3.1 Ballistic Coefficient Estimation Methodology

The orbit determination process uses a multi-day span of TLE data as position and velocity state observations to compute ballistic coefficient estimates and their corresponding uncertainty. The Fortran-based program FITLEO7 was used to assess how well the different atmospheric density models performed over three magnetic storm events. This program uses a batch least squares sequential filter with Bierman's UD method where U refers to the upper triangular factor, and D

the diagonal factor in a factorization of the filter error covariance matrix (Bierman, 1977). Force models include Earth Gravity Model 96 and World Geodetic System 84 (EGM96/WGS 84) Earth gravity, lunisolar attractions, solar radiation pressure and the widely used atmosphere density models, JB2008, NRLMSIS, and Jacchia 71. The orbit propagation precision of FITLEO7 has been verified with another numerical integration program TRACE (Warner et al., 2003), a well-maintained and documented trajectory and orbit determination tool at The Aerospace Corporation. The accuracy of FITLEO7 has also been tested by the TLE data of known well characterized decaying spheres (McVey and Chao, 2011). For TIEGCM data, a special Fortran subroutine (TIEGCM DENS) was created and tested to interpolate the logarithm of the density from the TIEGCM grid at a given time and point in space.

The chosen inactive space objects have low altitudes (~ 400 km or lower), where perturbations due to atmospheric drag are more prominent. The fitting process over the storm events produce a ballistic coefficient along with the radial, in-track and cross-track (RIC) residual error components. The in-track position error will have the largest value defining the error ellipsoid as the in-plane component, which the component error ratios can be about a 10 to 1 difference compared to the out-of-plane components (Peterson et. al., 2001). These residual errors are used as a metric to evaluate how well the TIEGCM model is performing relative to other widely used atmospheric density models.

Figures 1 and 2 are examples of the ballistic coefficient estimation and the uncertainties involved. The estimation technique yields valuable insight into the physical characteristics of the individual objects. For these examples and throughout the study, it is useful to represent the ballistic coefficient estimates in terms of the area-to-mass ratio (A/m), more specifically the A/m quantity multiplied by the drag coefficient. The drag coefficient is computed at the beginning of each orbit

determination fit span using an altitude-based model developed by Fraysse et. al. (2012). An automated version of FITLEO7 was used to create the A/m estimates as a function of time, as shown in Figures 1 and 2. The program marches through each day within the date range and provides an A/m estimate and in-track error residual over a span of 3 – 6 days of TLE data.

Figure 1 depicts the A/m estimates for object 4813 using the NRLMSIS atmospheric density model from Sept 1, 2003, through November 12, 2003, covering the Halloween event. The A/m estimates are expected to have a cross-sectional area variance due to the non-sphericity of the object, and an uncontrolled attitude relative to the velocity direction. The dashed blue line at $0.008 \text{ m}^2/\text{kg}$ is the average A/m estimate weighted by the residual error contributions. The yellow dotted line at $0.0073 \text{ m}^2/\text{kg}$ is the object A/m calculation based on pre-launch dimensions and mass information (Gunter's space page, 2023). The weighted average A/m agrees well with the A/m based on the object's physical dimensions, while providing a quantifiable metric to evaluate the individual A/m estimates. The in-track residual error spikes during the solar storm event around October 31, 2003, reflecting an increase in density model errors.

Figure 2 depicts the A/m estimates for object 4813 using the Jacchia-Bowman 2008 atmospheric density model from Sept 1, 2003, through November 12, 2003, covering the Halloween event. The individual A/m estimates have smaller high frequency movement compared to the NRLMSIS-2000 application of the same data set. The weighted average A/m estimate is $0.0076 \text{ m}^2/\text{kg}$, and the object A/m calculation is the same value as in Figure 1, of $0.0073 \text{ m}^2/\text{kg}$. The values of the weighted average A/m estimate are closer to the object A/m compared with the orbit determination process using the NRLMSIS model. The in-track error residual shows a similar spike near October 31, 2003 as in Figure 1.

4. In situ-density data

4.1 Challenging Minisatellite Payload (CHAMP)

The CHAMP satellite was launched on July 15, 2000 into a nearly circular, 87° inclination orbit with an initial altitude of 450 km. The precession period was 120 days. Over the mission lifetime the orbit decayed to 300 km before commencing reentry. The CHAMP satellite flew a version of the Spatial Triaxial Accelerometer for Research (STAR) provided by the Centre National d'Etudes Spatiales (CNES) and manufactured by the Office National d'Etudes et de Recherches Aerospatiales (ONERA) (Reigber and Schwintzer, 1995). The electrostatic forces required to keep a suspended proof-mass motionless were used to derive vehicle accelerations. The STAR instrument on CHAMP has a resolution of $3 \times 10^{-9} \text{ m/s}^2$. CHAMP was de-orbited in September of 2010. Densities were derived from accelerometer measurements by removing all non-drag forces and by using the relationship (see (1)) between satellite drag and atmospheric density (Bruinsma et al., 2004; Sutton, 2009). We used the density derived from CHAMP measurements where further bias corrections were made by Sutton et al. (2011) on the data received from CNES (Sutton et al., 2005; Häusler et al., 2007; Doornbos et al., 2010; Lieberman, 2013; Xiong et al., 2015).

4.2 Gravity field and Ocean Circulation Explorer (GOCE)

The GOCE satellite was launched in March 2009 in a 96.5° inclination, quasi dusk-dawn orbit. During the Science Mission phase from November 1, 2009 - October 20, 2013, it was maintained at mean altitudes between 275 km and 230 km. The thruster forces required to keep a suspended proof-mass motionless were used to derive vehicle accelerations. GOCE neutral density measurements, with a resolution of 80 km along the orbit and a precision of a few percent were obtained from the thruster data (Bruinsma et al., 2014).

5. Model to data comparisons

We compare model predictions with data for three geomagnetic storm events: October 2003, March 2013, and March 2015 storms, often referred to as the Halloween, St. Patrick's Day 2013, and St. Patrick's Day 2015 storms, respectively.

5.1. Halloween Day Storm

5.1.1. Description of storm

Figure 3 shows the time history of solar and geomagnetic indices used for the Halloween Storm calculations. Figure 1a shows the SYM-H and F107 indices. The SYM-H index is similar to the hourly Dst index but has a smaller time resolution of one minute (Iyemori et al., 1992). Figure 3b shows the three hourly values of the ap and Kp indices. The storm initial main phase started on 29 October 2003, at about 0540 UT with sudden southward turning of the interplanetary magnetic field (IMF) associated with a coronal mass ejection (CME) accompanied by extremely high speed solar wind flow of about 1900 km/s (Zurbuchen et al., 2004). The magnetosphere's response caused the SYM-H index to decrease to about -200 nT at the end of the "first" of a 3-step main phase. During the recovery phase of the first main phase, the IMF turned northward but at approximately 1400 UT on October 29, 2003, the IMF turned southward during the "second" main phase. Following the first CME, another hit the magnetosphere. This drove a "third" main phase and a minimum SYM-H of about -430 nT with very strong substorm-related activity in the ionosphere (Pulkkinen et al., 2005). A multiple-step (Richardson and Zhang, 2008) or two-step (Kamide et al., 1998) main phase development is not unusual for very large geomagnetic storms. On October 31, 2003, the low latitude edge of the visible aurora was observed at low (41° to 46°) geographic latitudes from the all sky camera in Hokkaido, Japan (Suzuki et al., 2005).

5.1.2. TIEGCM Simulation

We simulated the response to the storm by specifying a time history of Kp and F10.7. The simulation was done in two phases. The first phase was a conditioning “source run” to evolve the model default initial state to the conditions predicted before storm onset. The second phase was the “storm run” itself. For this simulation we used the TIEGCM in its default mode in which the heat and momentum sources are parametrized in terms of Kp and F10.7.

5.1.3. Predictions of density for the CHAMP orbit.

The model time step was 60 s and generated output at the same interval. The CHAMP satellite was then “flown” through the output fields and the data interpolated to the satellite position as it crossed selected latitudes.

Density was evaluated at the satellite position using the NRLMSIS empirical model and the predictions from both models were compared to the inferences of density based on the CHAMP acceleration data. The NRLMSIS model is the primary model used for density prediction in The Aerospace Corporation Astrodynamics Department. The daily average values of ap (Ap) are used for the NRLMSIS calculations.

5.1.4. Comparison results.

5.1.4.1. CHAMP data versus model predictions

Figure 4 shows the values of density derived from CHAMP data (red) and from CHAMP northbound flythroughs for NRLMSIS (blue) and the TIEGCM (green) for various latitude crossings versus UT from October 29, 2003 to November 4, 2003. Details differ across latitudes, but broadly the CHAMP data show a rapid rise from prestorm levels to a maximum value near the beginning of October 30 (here denoted Mx1). After October 30, the density diminishes to a minimum near noon on October 30 (Mn1), whence it rises to a second peak a few hours into October 31 (Mx2). The two peaks are of comparable value. After the second peak occurs, density

diminishes reaching an approximately level value around November 1. At some latitudes the data show a sharp peak a few hours into 29 November preceding the first broad peak. The main features seen in the CHAMP data are also seen in the NRLMSIS predictions and the phasing is similar on the whole. The amplitudes of the main peaks (those occurring near 30 and 31 October) are significantly underpredicted. The second main peak (the one peaking near 30 October) can lead CHAMP by several hours, depending on latitude. A notable difference is that the deep minima between these maxima is much shallower in the NRLMSIS predictions than seen in the CHAMP data, giving a large overprediction. The post-storm diminishment of NRLMSIS density is much slower and decays to much larger value than is observed.

The TIEGCM density predictions resemble the variations in the observed density except that the peaks tend to be under predicted and the trough between the peaks is overpredicted. The phasing is good, except at high latitudes where it is shifted a few hours later. The post storm values agree well with the observations. The overall bias with respect to the observations is less for the TIEGCM predictions than for the NRLMSIS predictions: there is a greater tendency for the TIEGCM to split the difference between peaks and the trough. To see the effects on drag in an orbit averaged sense we look at errors in orbital prediction.

5.1.4.2. Errors in orbital determination

Three different inactive decaying satellites were selected from the catalog in October 2003 during the super storm in October 2003. Their TLE ID and orbit parameters are:

- 04813: mean altitude: 291 km, inclination: 81.1°
- 4393: mean altitude: 316 km, inclination: 81.2°
- 11630: mean altitude: 363 km, inclination: 81.2°

The fitting program FITLEO7 read the TLE data with starting date on October 29, 2003 and fit the following 6 days of data of the super geomagnetic storm. FITLEO7 generates position errors or residuals along radial, in-track and cross-track directions during the 6-day fit. The residuals resulting from using the TIEGCM are compared with those using the three empirical models.

Tables 1, 2 and 3 show the 1σ residuals for the three directions for each of the three satellites. The largest errors by far are the in-track errors, being about an order of magnitude greater than either the radial or cross-track errors. For each of these satellites the TIEGCM and JB2008 in-track errors are, on the whole, moderately less than for NRLMSIS and significantly less than for Jacchia 71. The TIEGCM and JB2008 models perform about the same. The relative performance for the radial direction is the same as for the in-track errors. The radial residuals are about half the in-track errors for object 04813 about a third for object 11630. For object 4393 the ratio is highly variable, ranging from about one half for Jacchia to about one-fifth for the TIEGCM. Similar remarks apply to the cross-track error with respect to the relative performance among models. However, the residuals are smaller than the radial residuals, by about a factor of two for object 04813 and are similar for objects 11630 and 4393. The NRLMSIS model consistently outperforms Jacchia 71 for these three objects.

Table 1.
Summary of 6-day fit results (4813) with mean altitude 291 km

Density Model	Estimated A/m [m ² /kg]	1σ residual radial [km]	1σ residual in-track [km]	1σ residual cross track [km]
TIEGCM	0.00769	3.43	12.5	1.55
JB2008	0.00824	4.97	13.0	2.79
MSIS2000	0.00580	3.90	12.8	2.06
Jacchia 71	0.00518	3.74	14.1	2.08

Table 2.
Summary of 6-day fit results (4393) with mean altitude 316 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00675	0.969	4.30	0.683
JB2008	0.00800	0.695	4.18	0.478
MSIS2000	0.00488	1.73	6.06	1.38
Jacchia 71	0.00406	3.02	6.67	2.40

Table 3.
Summary of 6-day fit results (11630) with mean altitude 363 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00617	0.650	2.20	0.457
JB2008	0.00678	0.680	2.74	0.543
MSIS2000	0.0500	1.14	4.03	0.871
Jacchia 71	0.00383	2.56	6.30	1.95

Figure 5 shows the intrack residual errors of the 6-day fits shown in Tables 1-3. The plots for the three objects show graphically what was noted above: the performance for the TIEGCM and JB2008 are comparable and both show a modest improvement with respect to NRLMSIS and a more significant improvement with respect to Jacchia71.

5.2. St. Patrick's Day Storm 2013

5.2.1. Description of storm

Figure 6 shows the time history of solar and geomagnetic indices used for the St. Patrick's Day calculations. The top panel shows the Kyoto SYM-H and F107 indices. The bottom panel shows the three hourly values of the ap and Kp indices. The daily average values of ap (Ap) are used for the NRLMSIS calculations. On March 17, 2013, at 6:28 UT, a CME passed by NASA's Advanced Composition Explorer (ACE) as it approached Earth. Upon impinging on the magnetosphere, the CME caused a geomagnetic storm (https://www.nasa.gov/mission_pages/sunearth/news/News031513-cme.html). The SYM-H index dropped to -132 nT at 21:00 UT on March 17 and then started to slowly recover. The Ap values increased after the sudden commencement to a

maximum of 72 on March 17 during two $K_p = 7$ and four $K_p = 6$ intervals, indicating a major geomagnetic storm (Cander, 2019). Equatorward expansion of the auroral oval to mid latitudes, observed from ground-based and satellites, occurred mainly during the convection mode (Lyons et al., 2016).

5.2.3. Comparison Results

5.2.3.1. GOCE data versus model predictions

Figure 7 is similar to Figure 4 but for GOCE data instead of CHAMP data that were not available for the March 2013 event. The figure shows the values of density derived from GOCE data (blue) and from GOCE northbound flythroughs for NRLMSIS (blue) and the TIEGCM (orange) for various latitude crossings versus UT day-of-year for 2013.

The density is shown beginning two days before the onset of the storm. All three pre-onset variations are similar, with a significant tendency for NRLMSIS to be biased high in the day preceding onset. Around 6 hours into March 17 GOCE density rises rapidly and quickly evolves into a highly structured series of fluctuations culminating with a peak occurring early in March 18. The NRLMSIS variation of density, on the other hand, is a highly smoothed version of the measured density that is biased high. The onset of the NRLMSIS storm time variation is shifted several hours early with respect to the GOCE onset and attains much higher values of density throughout the main part of the storm response.

Except at the two highest latitudes shown, the phasing of the TIEGCM variation agrees reasonably well with the phasing of the GOCE observations. It is biased high, but since it is high when GOCE is high, it appears to have a smaller bias than NRLMSIS, which attains its largest values before the GOCE show significant amplitudes. At the two highest latitudes, the TIEGCM density

predictions show little coherence with the GOCE observations except for the last GOCE peak, which is nicely in phase with TIEGCM results.

To see the effects on drag in an orbit averaged sense we again look at errors in orbital prediction.

5.2.3.2. Errors in orbital determination

Three inactive decaying satellites were selected from the space catalog in 2013. Their TLE ID and orbit parameters are:

- 28770: mean altitude: 316 km, inclination: 63.3°
- 27291: mean altitude: 360 km, inclination: 97.7°
- 26953: mean altitude: 417 km, inclination: 97.2°

The FITLEO7 program read the corresponding TLE data with starting date March 15, 2013 and fit the following 5 days of data, which includes the geomagnetic storm occurring 3 to 4 days from the selected starting epoch (Figure 6). FITLEO7 generated position errors or residuals along radial, intrack and cross-track at the end of the 5-day orbit determination. The residuals resulting from using TIEGCM are compared with those using other density prediction models as shown in Tables 4, 5 and 6 for the three decaying satellites.

Table 4.
Summary of 5-day fit results (28770) with mean altitude 317 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00942	0.796	4.42	0.827
JB2008	0.00800	0.973	5.52	0.954
MSIS2000	0.00886	0.0581	8.65	0.405
Jacchia 71	0.00916	0.545	7.79	0.401

Table 5.
Summary of 5-day fit results (27291) with mean altitude 360 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00570	0.268	1.24	0.271
JB2008	0.0180	0.278	4.12	0.403
MSIS2000	0.0221	0.223	3.75	0.322
Jacchia 71	0.0187	0.181	5.71	0.420

Table 6.
Summary of 5-day fit results (26953) with mean altitude 417 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.0101	0.140	0.916	0.218
JB2008	0.00622	0.145	1.36	0.411
MSIS2000	0.00896	0.123	1.00	0.156
Jacchia 71	0.00767	0.128	1.07	0.165

Again, the largest error by far is the intrack error. The comparisons consistently show that for intrack error orbit determination solutions using TIEGCM densities are better than for any of the empirical models. Among the empirical models, there is little consistency with respect to relative in-track errors. NRLMSIS performs best for two of the three objects (27291 and 26953) and JB2008 for the third (28770). The Jacchia model does not perform best for any of the three objects, but does outperform NRLMSIS for objects 28770 and 27291 and JB2008 for 226953. Overall, the intrack performance among the three empirical models is comparable.

Radial and cross-track residuals are again much smaller than intrack, being from on the order of a factor of five to a factor of ten, or more, smaller. The two residual sets are comparable in magnitude with no significant and consistent systematic variations among models evident.

Figure 8 gives a clear illustration by comparing the dominant error along the intrack direction. The most striking features of the plots are the better performance of the TIEGCM over any of the empirical models. There is modestly better performance for NRLMSIS relative to JB2008 for two of the three objects, and a better performance overall for JB2008 relative to Jacchia 71.

5.3. *St. Patrick's Day Storm 2015*

5.3.1 *Description of storm.*

Figure 9 shows the time history of solar and geomagnetic indices used for the St. Patrick's Day 2015 calculations. The SYM-H and F10.7 indices are shown in Figure 9a and the three hourly Kp and ap indices are shown in Figure 9b. The March 17, 2015 storm, the strongest storm of Solar Cycle 24, was caused by a CME that occurred at 0200 UT on March 15, 2015. The storm main phase lasted about 18 hours and developed in two steps. The southward IMF in the sheath region drove the first step during which SYM-H dropped to about -100 nT (Kataoka et al., 2015). The southward IMF in the magnetic cloud drove the second step of the main phase with a minimum SYM-H of about -230 nT. Citizen observations of visible aurora for the March 2015 storm at low latitudes were reported by Case et al. (2014) to be lower than predicted from the Newell (2010) and Roble and Ridley (1987) models.

5.3.2. *Errors in orbital determination*

Three inactive decaying satellites were selected from the space catalog in 2015. Their TLE ID and orbit parameters are:

- 40311: mean altitude: 293 km, inclination: 96.5°
- 39262: mean altitude: 324 km, inclination: 96.6°
- 13120: mean altitude: 431 km, inclination: 81.1°

The FITLEO7 program read the corresponding TLE data with starting date March 16, 2015 and fit the following 5 days of data, which includes the geomagnetic storm occurring 2 days from the selected starting epoch (Figure 8). FITLEO7 generated position errors or residuals along radial,

intrack and cross-track at the end of the 5-day orbit determination. The residuals resulting from using TIEGCM are compared with those using other density prediction models as shown in Tables 7, 8 and 9 for the three decaying satellites.

Table 7.
Summary of 6-day fit results (40311) with mean altitude 293 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00815	5.39	15.6	2.58
JB2008	0.00698	8.91	28.1	4.25
MSIS2000	0.00766	8.46	22.5	4.09
Jacchia 71	0.00688	11.7	28.0	5.63

Table 8.
Summary of 6-day fit results (39262) with mean altitude 324 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00840	0.360	8.29	1.81
JB2008	0.00687	0.496	15.4	2.63
MSIS2000	0.00767	0.600	10.7	3.33
Jacchia 71	0.00668	0.838	10.5	4.74

Table 9.
Summary of 6-day fit results (13120) with mean altitude 431 km

Density Model	Estimated A/m [m ² /kg]	1 σ residual radial [km]	1 σ residual intrack [km]	1 σ residual cross track [km]
TIEGCM	0.00970	0.238	1.15	0.208
JB2008	0.00763	0.142	1.53	0.171
MSIS2000	0.00947	0.141	1.69	0.148
Jacchia 71	0.00761	0.148	1.47	0.161

For all three objects the TIEGCM has the smallest intrack residuals. The results for object 39262 are unique in that among the empirical models JB2008 performs least well for two of the three objects (40311 and 39262). For object 40311, NRLMSIS intrack residuals are notably smaller than for JB2008 or Jacchia 71 and for object 39262 the residual for JB2008 is notably larger than for

the other two empirical models. Otherwise, the differences among the empirical models are not significant. The radial and crosstrack residuals are on the order of factors of five to ten, or more, smaller than intrack residuals. For objects 40311 and 39262, the residuals for the TIEGCM are significantly smaller than for any of the empirical models. For object 39262, JB2008 is significantly smaller and Jacchia significantly larger than for the other two empirical models.

The radial and crosstrack residuals for object 13120 are all small and of doubtful significance, likewise for the radial residual for object 39262. The cross track residual for object 39262 and both radial and crosstrack residuals for object 40311 are comparatively large. They both show the same ordering in terms of increasing residuals, ordered as TIEGMC, JB2008, NRLMSIS and Jacchia 71.

Figure 10 shows the bar chart for intrack errors. Only for the two lowest objects where density is largest and drag is greatest (all objects have similar A/m ratios) is there a meaningful ordering. In terms of increasing residuals the ordering is TIEGCM, NRLMSIS, Jacchia 71 and JB2008, though the ordering of the last two is based on a single object (39262).

6. Discussion

We note that the two objects with mean orbital altitudes above 400 km (see Tables 6 and 9) showing (as expected) the smallest intrack residuals, have similar residuals and show variations among the models that are small, and which do not reflect the variations at lower altitudes for the same event. This suggests that at these higher altitudes the intrack residuals are dominated by errors in the tracking data, rather than by errors attributable to imperfect modeling of drag. The intrack residuals for these two objects are $\sim 1.0 - 1.5$ km. For objects with mean orbital altitudes below 400 km, residuals plausibly attributable to TLE errors are usually much smaller than the total residual, but in two cases the TLE contributions are similar to the total residuals. These

instances are shown in Tables 3 (object 11630 with mean altitude 363 km) and 5 (object 27291 with mean altitude 360 km) where the TIEGCM intrack residuals were comparable to or only marginally larger than the residuals attributable to TLE errors, suggesting that the predictions in these cases were at or near the limit of irreducible error. We also note that the median TLE error has been reported to have decreased around 2013-2014 (Hejduk et al., 2013).

Whereas the empirical models we have discussed are based on historical data sets, an alternative approach has been developed that includes real time assimilation of tracking data to correct the density predictions of a model in the Jachhia family of empirical models (Storz et al., 2005). The HASDM is an assimilative extension of the Jacchia (1970) model. The HASDM uses calibration satellite observations assimilated in real time to make corrections to its background Jacchia model. HASDM is not available for public use, however recently historical output sets of global density have been publically released (Tobiska et al. 2021) and analyzed (Licata et al., 2021). This database contains data for the years 2000 to 2019. These data along with JB2008 were compared to CHAMP and Gravity Recovery and Climate Experiment (GRACE-A) measurements for the Halloween Storm of 2003. The GRACE-A satellite, like CHAMP flew a high precision accelerometer, but at higher altitudes, ranging between 460 and 540 km. The mean orbit averaged model-to-measurement differences (bias) for CHAMP were found to be 26% and 37% for HASDM and JB2008, respectively. The corresponding values for GRACE-A were 16% and 36% for HASDM and JB2008. Thus, the use of data assimilation gave significantly smaller mean errors. The most dramatic improvement in relative terms occurred at GRACE-A altitudes where drag effects in absolute terms are much smaller. Figure 11 shows the CHAMP, TIEGCM, and NRLMSIS densities and percentage difference of TIEGCM and NRLMSIS densities relative to CHAMP along the CHAMP orbit from October 19, 2003 to November 5, 2003. We found mean

508 storm-time model-to-measurement relative errors for TIEGCM to CHAMP of 19% and NLRMSIS
509 to CHAMP of 31%. Thus, TIEGCM has a lower mean relative error to CHAMP density than the
510 HASDM model reported by Licata et al. (2021) for this storm.

511 The TIEGCM is a first principles model in that the code integrates the equations of motion and the
512 ionosphere and electrodynamics are based on physical principals, but in a simplified form with
513 heavy reliance on empirically based parameterizations (Roble and Ridley, 1987). TIEGCM
514 addresses density variations in the high drag region below $\sim 500 - 700$ km, and not above.
515 Parameterized schemes relevant to magnetic storms include the large-scale convection electric
516 field, auroral oval (configuration, and particle fluxes and electric field) (Roble et al., 1982;
517 Richmond et al, 1992; Heelis et al., 1982; Weimer, 2001). To derive the ionization rate as a
518 function of height an analytic relationship derived for a monoenergetic and monodirectional
519 electron beam was used (Lazarev, 1967). None of these schemes allows for an interaction between
520 the thermosphere-ionosphere system and the magnetosphere where the electric fields and particle
521 fluxes originate.

522 Significant improvements in first principles models that rely on similar parametrizations are likely
523 to result from interactive coupling to magnetospheric models, using more detailed transport models
524 of the interaction between particle fluxes and the atmosphere (Strickland, 1993) and using
525 ionospheric models where simplifying assumptions are relaxed. Parameterized schemes have the
526 same limitations as empirical models, namely, a parameter input list completely characterizes the
527 output. In reality, there is an irreducible error that originates in the statistical nature of
528 parameterized schemes, namely that each parameter value represents an ensemble of states.
529 Substantial progress beyond this limitation can come only from minimizing reliance on
530 parameterized schemes.

The success of numerical weather prediction and HASDM shows the value of real-time data assimilation. Data assimilation can be used to better constrain initial conditions or to continually adjust the solution as new data are assimilated (Navon, 2009). The challenge in first principles models is to maintain dynamical consistency (avoid spurious transients). A new data assimilative filter in the TIEGCM that estimates external drivers such as F10.7 and Kp and reinitializes the thermosphere-ionosphere model for a past history sufficient to account for time scales of the thermospheric changes shows promise for reducing root mean square errors relative to neutral density observations (Sutton et al., 2018).

The main disadvantage of first principle models such as the TIEGCM relative to empirical models is processing speed. In terms of data processing speed in this evaluation, the representation of the density data is extremely inefficient with huge storage files, resulting in extremely slow computation, 100 times slower than using any of the empirical density models. Approaches to alleviating this shortcoming include more efficient representation of model output files (spherical harmonic representations, for example) to significantly improve data processing. The number of files may be reduced by efficient schemes for temporal interpolation, by use of, for example, Chebychev polynomials.

7. Summary and Conclusions

The main finding of this study is that even with heavily parameterized schemes to specify energy and momentum sources, a first principles model outperforms widely used empirical models. With greater generality and less reliance on parameterized schemes, these models have the potential for reducing errors under highly disturbed conditions to levels that do not significantly degrade orbit determination.

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Data Availability Statement:

The ap and Kp indices are available from https://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html or <https://www.gfz-potsdam.de/en/kp-index>, *SYM-H* from *NASA OMNIWeb* https://omniweb.gsfc.nasa.gov/ow_min.html (Papitashvili et al., 2020), and F10.7 from https://kp.gfz-potsdam.de/app/files/Kp_ap_Ap_SN_F107_since_1932.txt. We obtained the CHAMP neutral density data for the October 2003 storm and the GOCE neutral density data for the March 2013 storm from Dr. Eric Sutton. The TLE data for the decayed satellites used in this study were obtained from <http://Space-Track.org>. TIEGCM simulation data for the three storms and data used in the figures in this study, including the CHAMP and GOCE data, are available at (Walterscheid et al., 2022). The NCAR TIEGCM is available at <http://www.hao.ucar.edu/modeling/tgcm/tie.php>. All data are cited and/or acknowledged.

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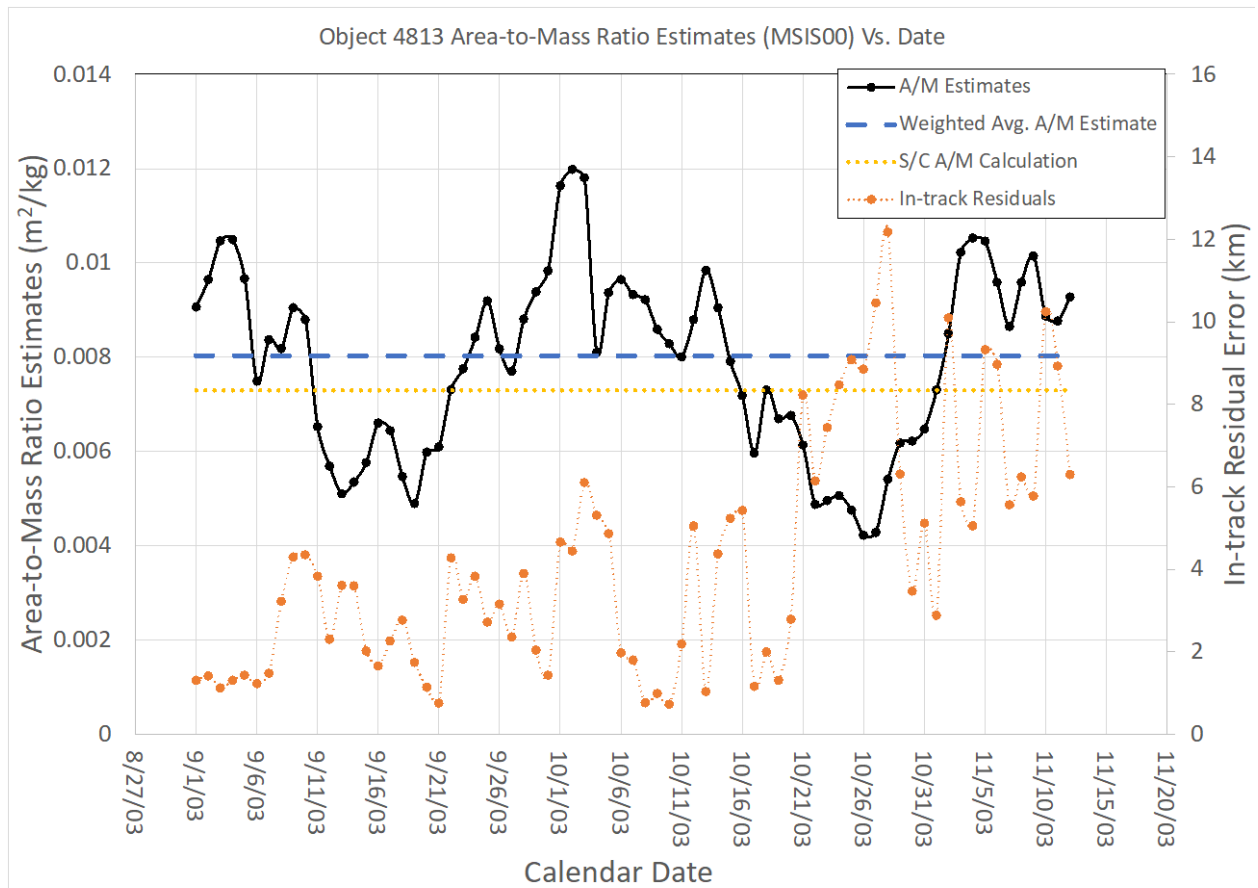


Figure 1. The A/m estimate history of object 4813 using the NRLMSIS model.

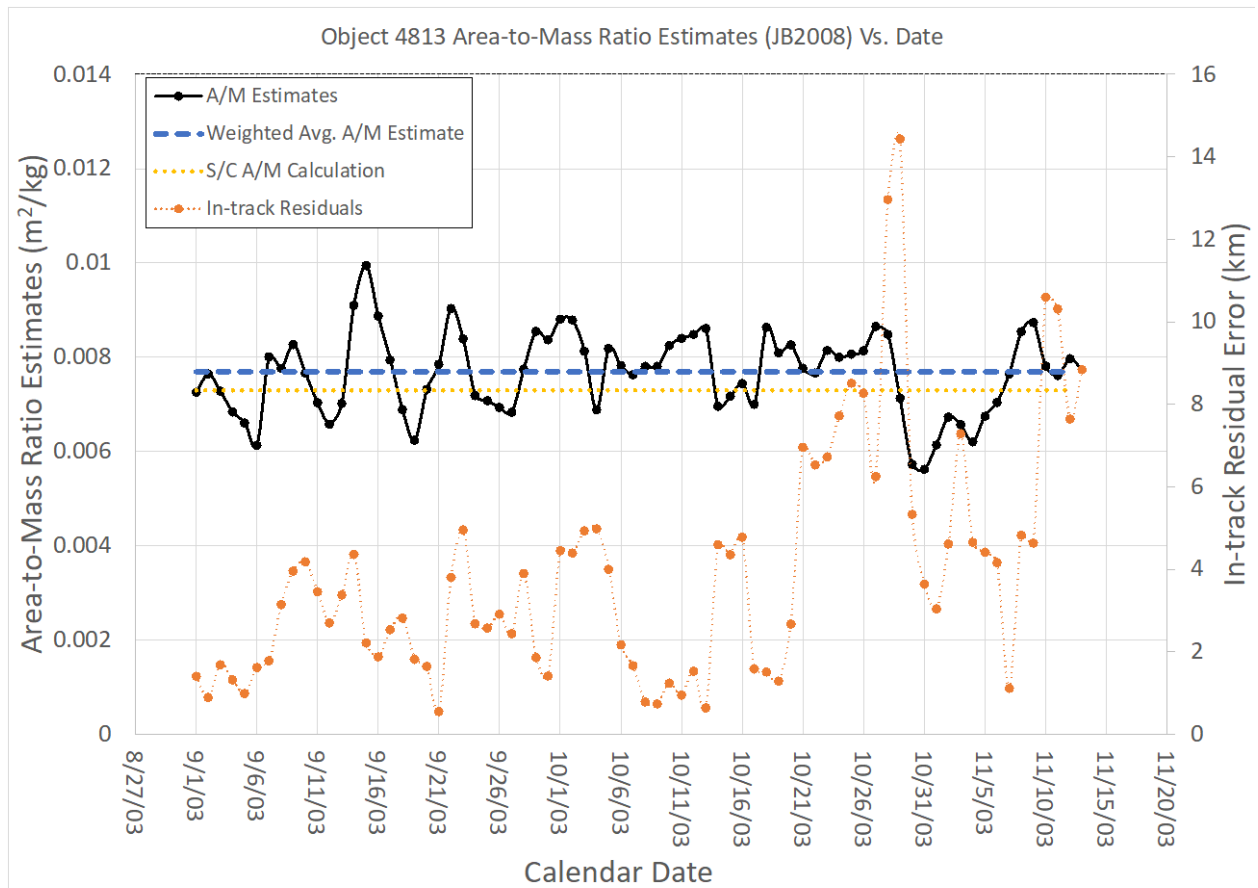


Figure 2. The A/m estimate history of object 4813 using the Jacchia-Bowman 2008 model.

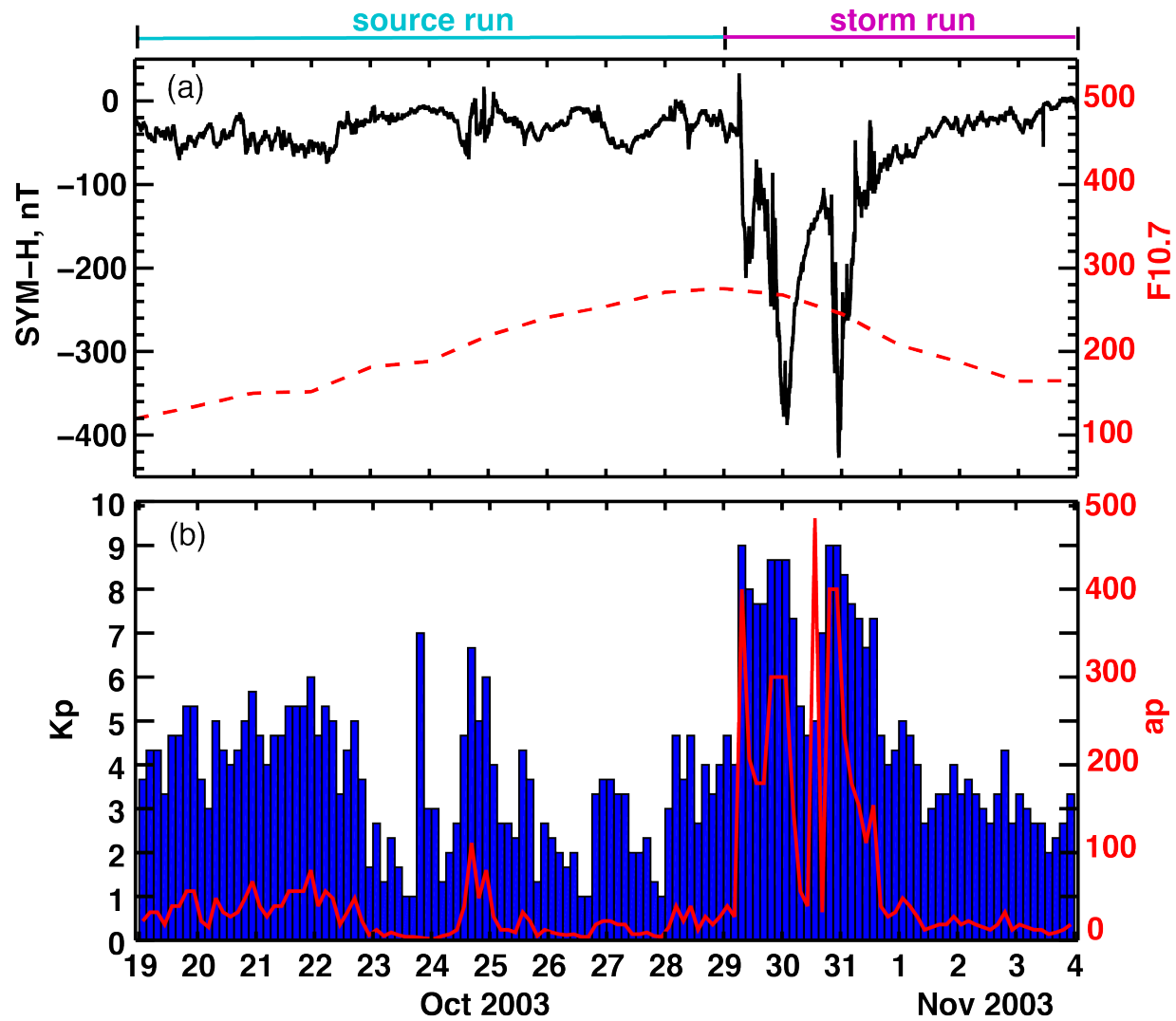


Figure 3. Time history of solar and geomagnetic indices used for Halloween Storm calculations. Panel (a) shows the SYM-H (black curve) and F107 indices (red dashed curve). Panel (b) shows the ap (red curve) and Kp (blue bars) indices.

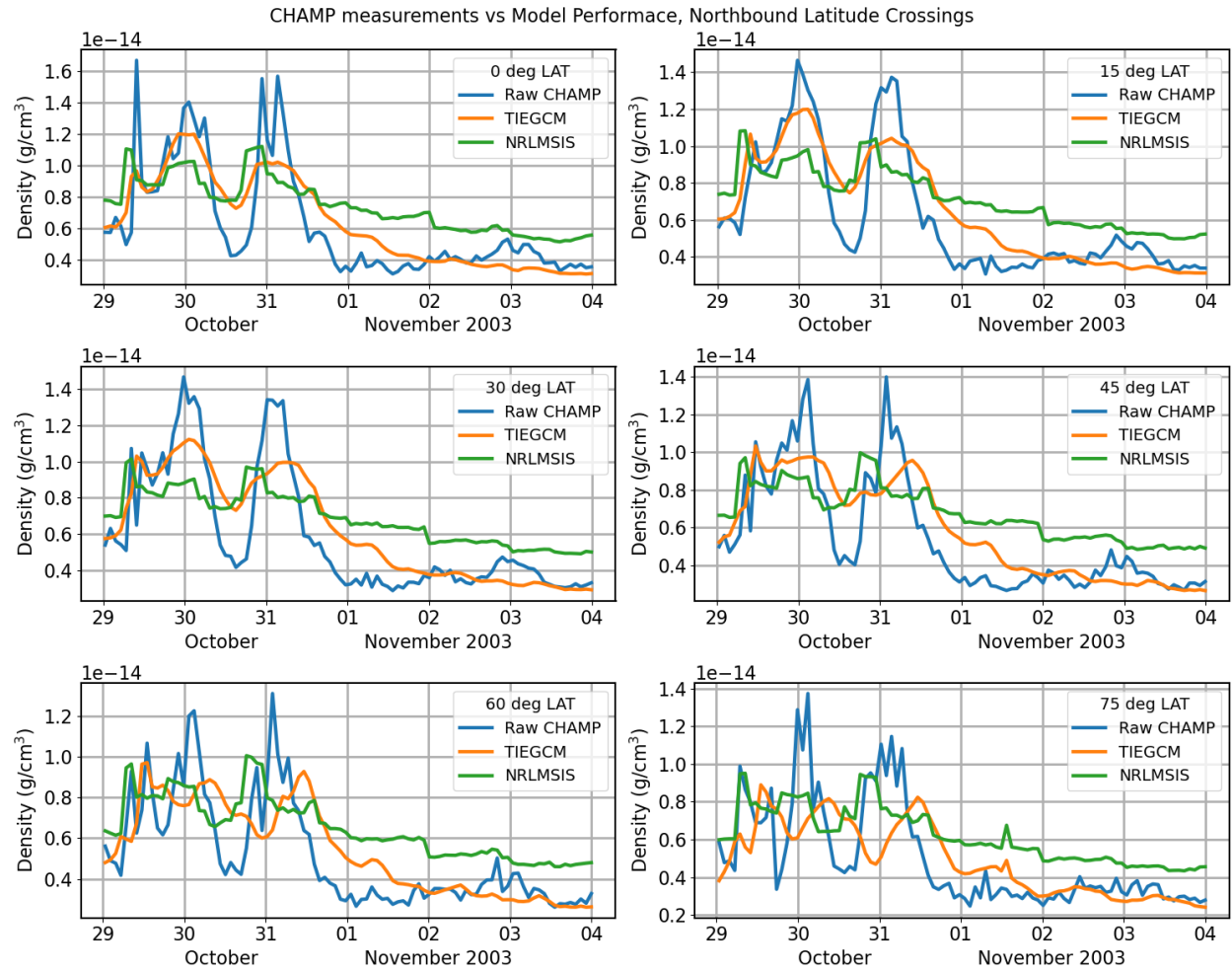
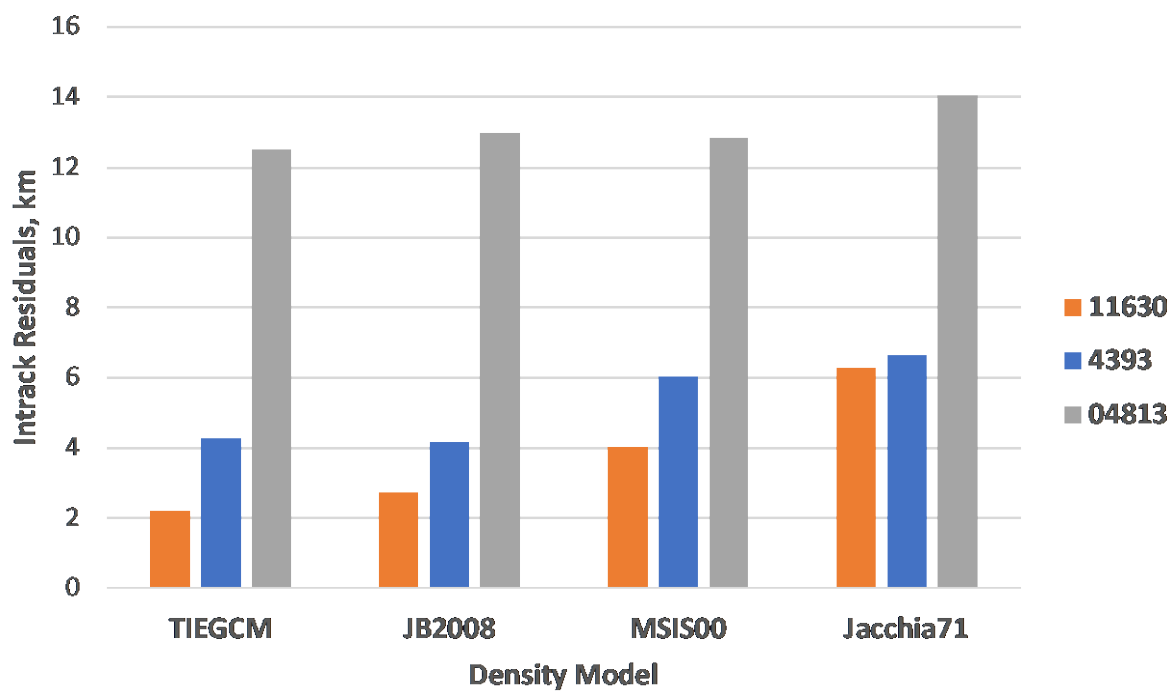


Figure 4. Comparison of NRLMSIS, TIEGCM density to CHAMP measurements at the CHAMP satellite.

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Figure 5. Comparison of RMS intrack residual errors (5-day fit of TLE data). The mean altitudes for the three objects were 04813 (blue), 291 km; 4393 (orange), 317 km; and 11630 (grey), 363 km. The inclinations of all three objects were similar ($\sim 81^\circ$ to 82°).

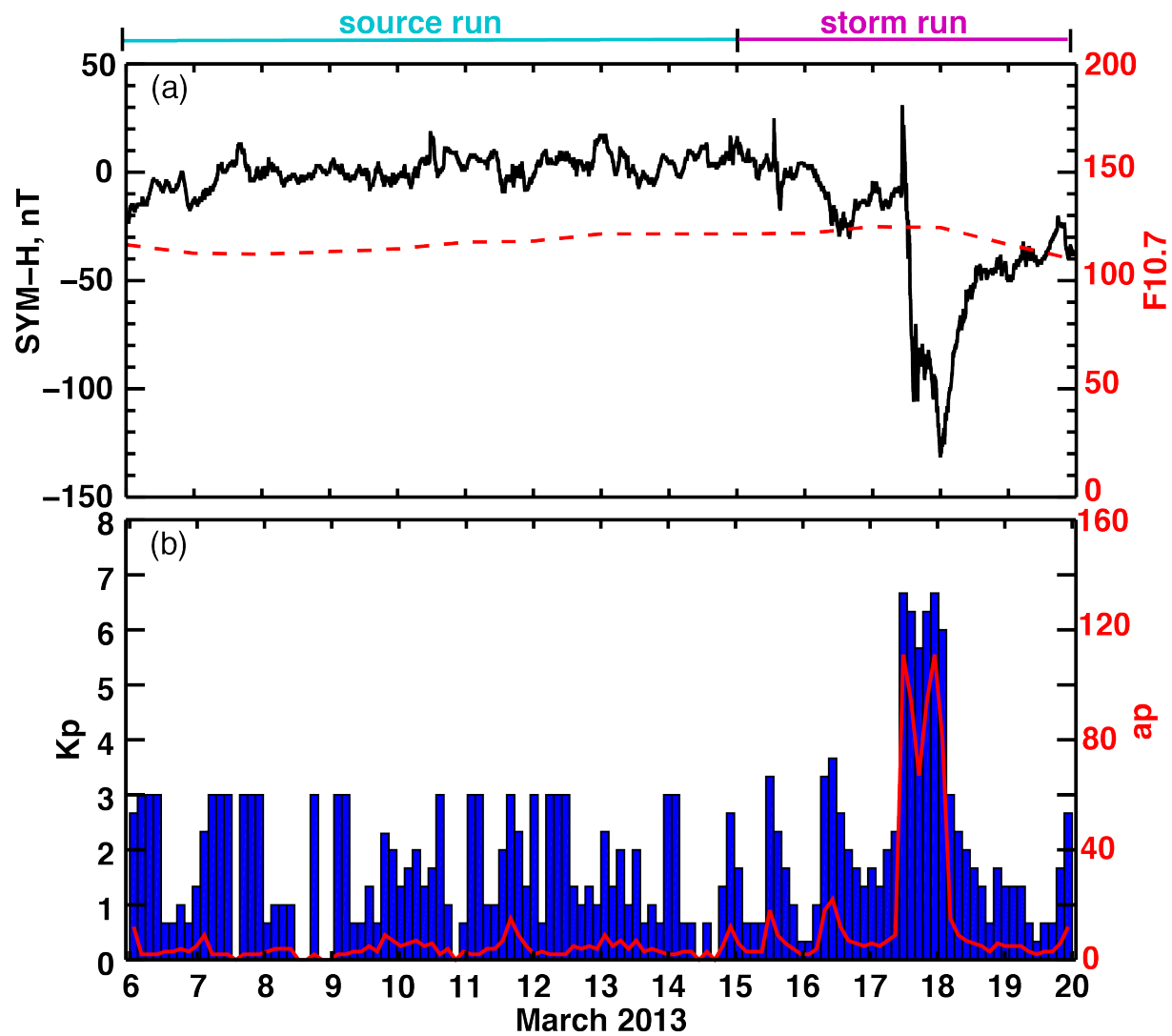


Figure 6. Time history of solar and geomagnetic indices used for the St. Patrick's Day Storm calculations. The top panel shows the SYM-H and F107 indices. The bottom panel shows the ap and Kp indices.

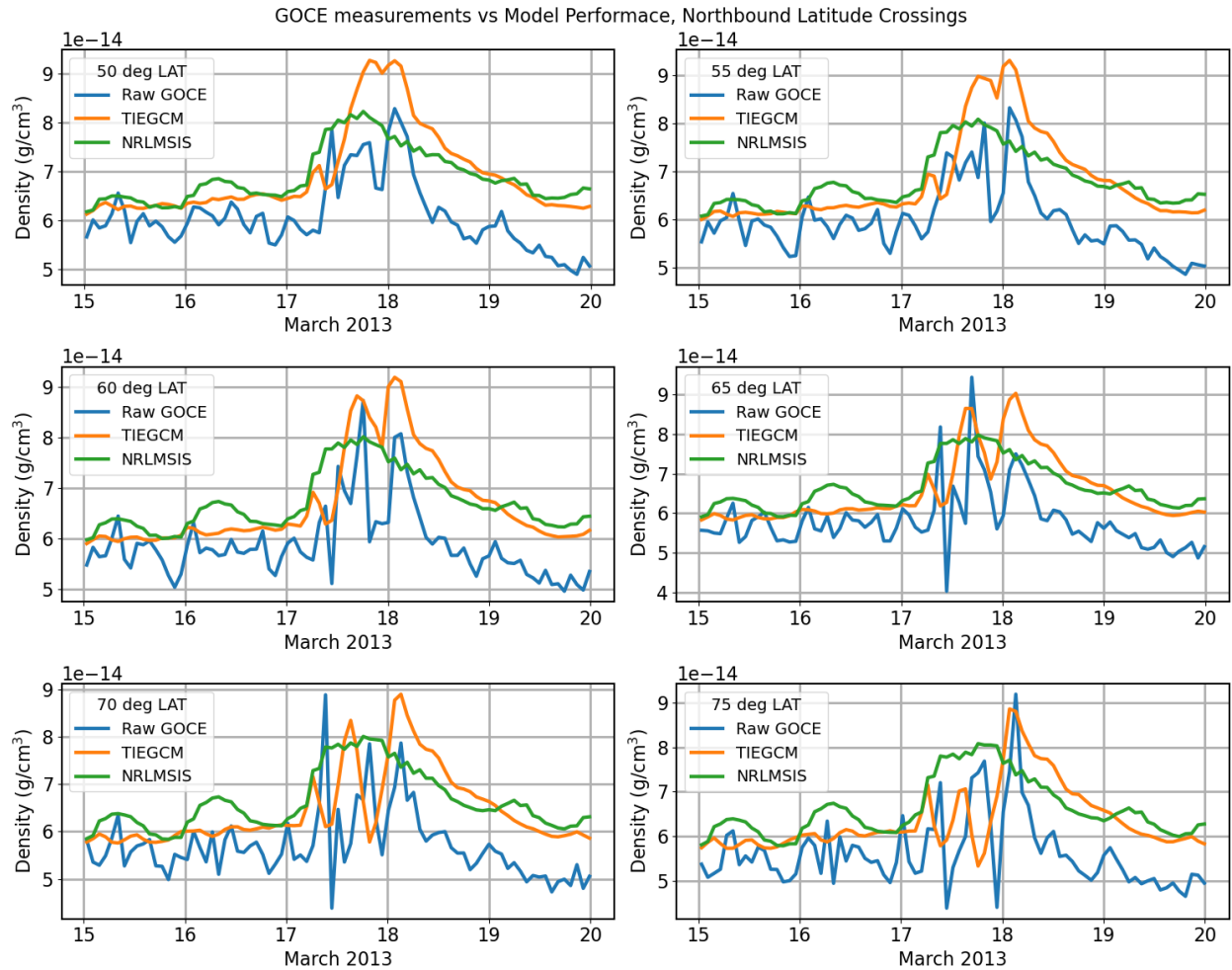


Figure 7. The values of density derived from GOCE data (blue) and from GOCE northbound flythroughs for NRLMSIS (green) and the TIEGCM (orange) for various latitude crossings versus UT day-of-year for 2013. The days are from March 15, 2013 to March 20, 2013.

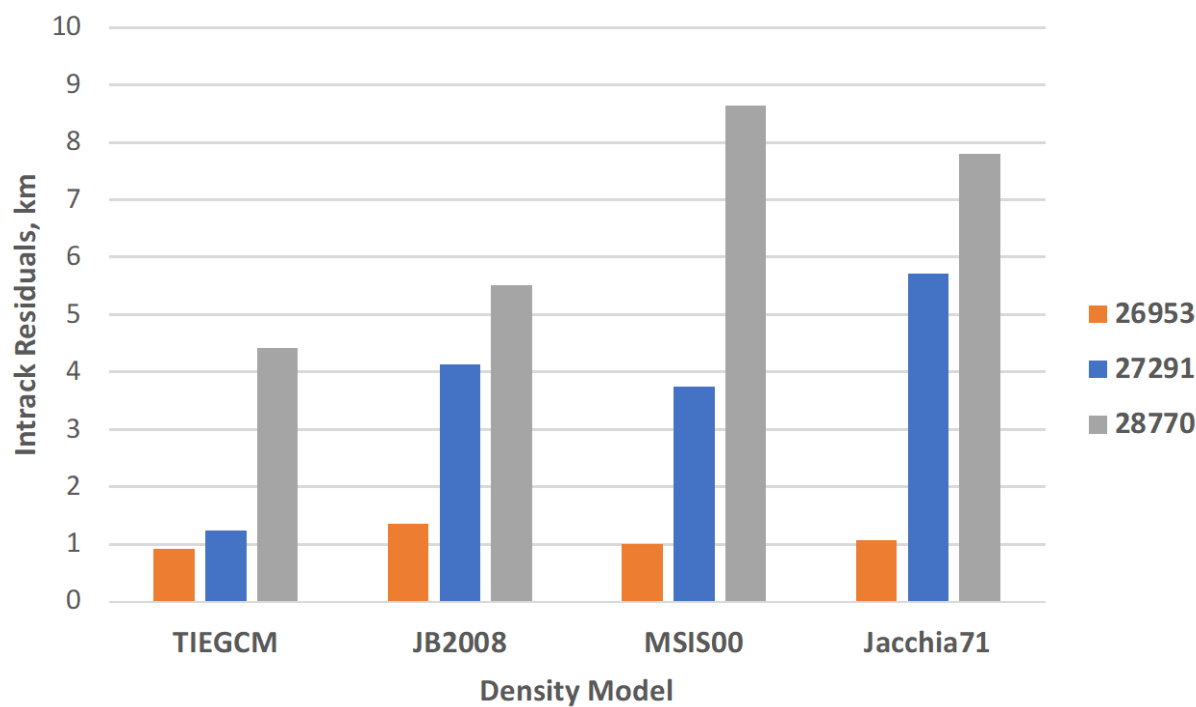


Figure 8. Comparison of RMS intrack residual errors (5-day fit of TLE data) for the March 2013 storm. The mean altitudes for the three objects were 28770 (grey), 317 km; 27291 (blue), 360 km; and 26953 (orange), 417 km. The inclinations of objects 288770, 27291, and 26953 were ~63°, 98°, and 97°, respectively.

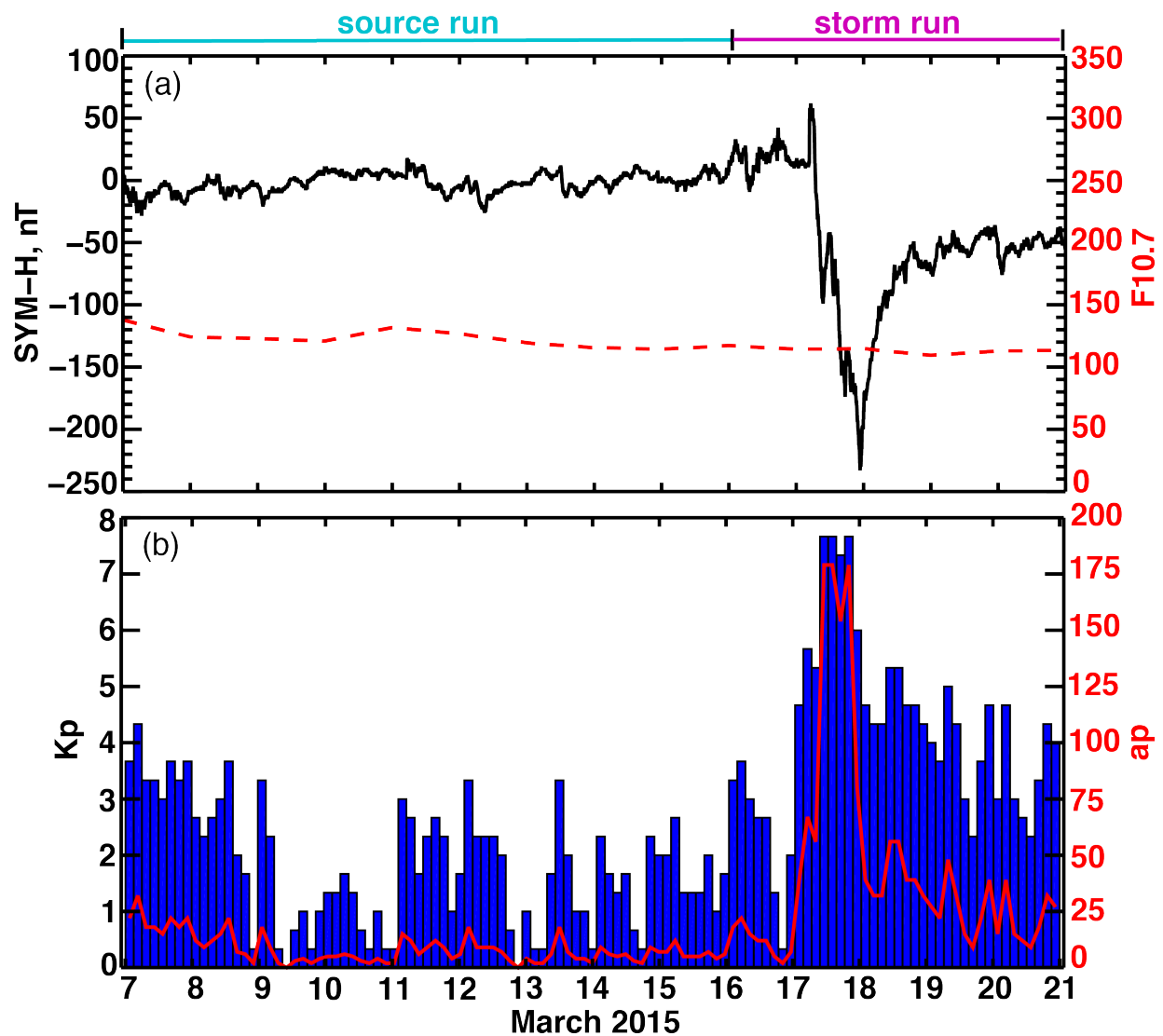


Figure 9. Time history of solar and geomagnetic indices used for the March 2015 storm calculations. The top panel shows the SYM-H and F107 indices.

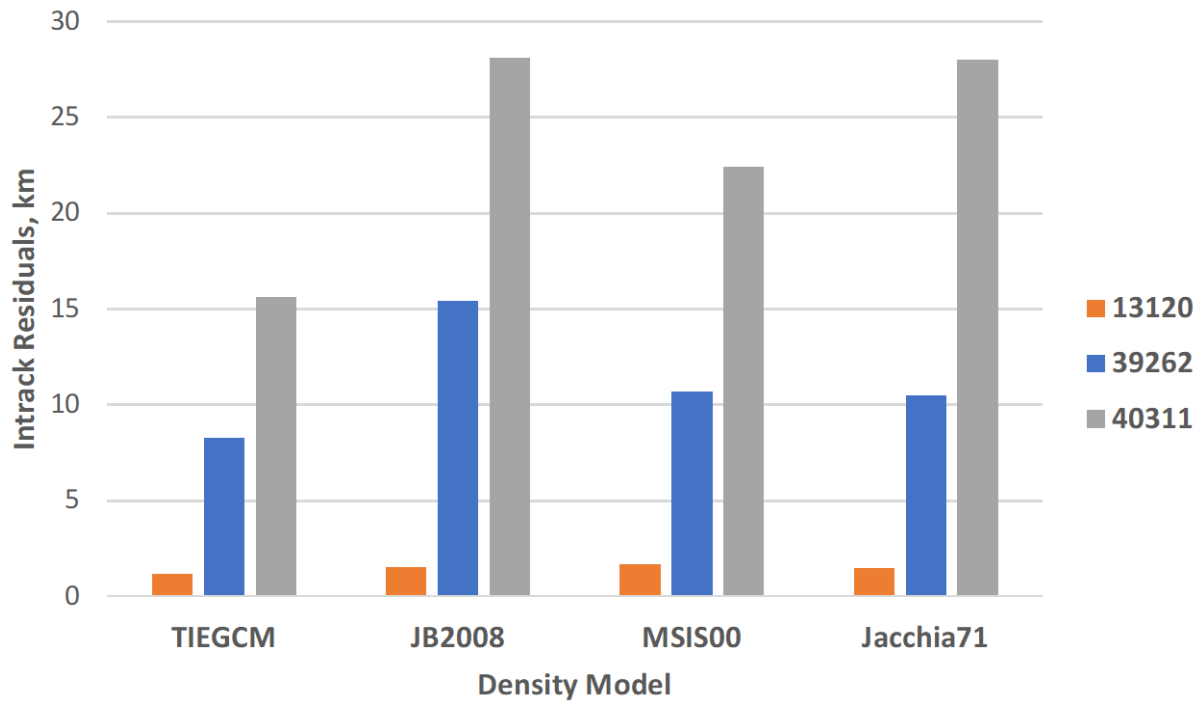


Figure 10. Comparison of RMS intrack residual errors (5-day fit of TLE data) for the March 2015 storm. The mean altitudes for the three objects were 40311 (grey), 293 km; 39262 (blue), 324 km; and 13120 (orange), 394 km. The inclinations of objects 40311, 39262, and 13120 were $\sim 97^\circ$, 97° , and 81° , respectively.

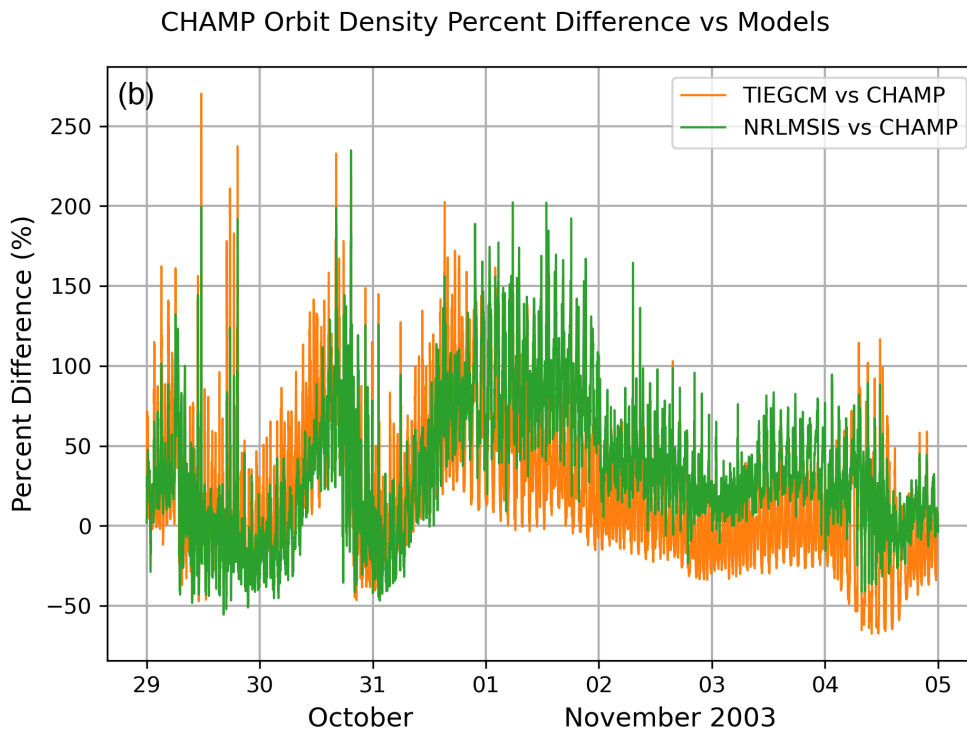
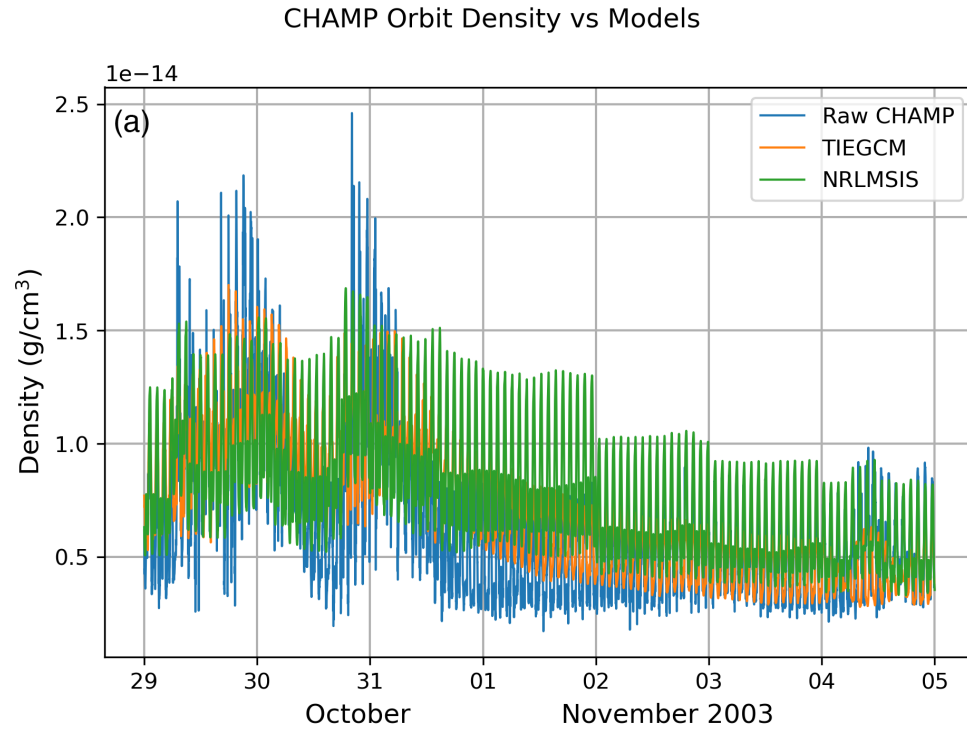


Figure 11. (a) CHAMP (blue curve), TIEGCM (orange curve), and NRLMSIS (green curve) density along the CHAMP orbit during October 29, 2003 to November 5, 2003. (b) The percentage difference of TIEGCM to CHAMP and NRLMSIS to CHAMP densities are shown by the orange and green curves, respectively.