Error Analysis of Typical Thermospheric Density Models (Postprint)

Authors: Liu Wei, Wang Ronglan, Siqing Liu, Gong Jiancun

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Abstract

Using thermospheric density data derived from accelerometer measurements on the CHAMP satellite during the 2755-day period from 2001-05-15 to 2008-12-31 as a benchmark, a statistical analysis of the errors of the JB2008 and MSISE-00 models was conducted. It was found that both models generally overestimated thermospheric density, but the accuracy of JB2008 was superior to that of MSISE-00, with the JB2008 model having a mean relative error of 2.2% and the MSISE-00 model having a mean relative error of 17.6%. After briefly classifying the space environment and statistically analyzing the latitude and local time characteristics of measured and modeled thermospheric densities under various types of events, it was found that the MSISE-00 model exhibits better local time characteristics, while the JB2008 model exhibits better latitude characteristics. This study holds certain significance for refining our understanding of the error characteristics of current thermospheric density models and their directions for improvement.

Full Text

Typical Thermospheric Density Model Error Analysis

LIU Wei, WANG Ronglan, LIU Siqing, GONG Jiancun
(National Space Science Center, Chinese Academy of Sciences, Beijing 100190)

Abstract

Using 2755 days of accelerometer-derived thermospheric density data from the CHAMP satellite during 2001-05-15 to 2008-12-31 as a benchmark, we performed statistical analysis of errors in the JB2008 and MSISE-00 models. Both models generally overestimated thermospheric density, but JB2008 demonstrated superior accuracy compared to MSISE-00, with mean relative errors of 2.2% and 17.6%, respectively. We classified the space environment into four categories based on simple and commonly available model inputs—the solar radiation index f10.7 and geomagnetic index Ap—and statistically characterized the latitude and local time dependencies of measured and modeled densities under each environment type. The results reveal that MSISE-00 exhibits better local time characteristics, while JB2008 shows superior latitude characteristics. This study provides valuable insights for refining our understanding of current thermospheric density model error characteristics and identifying directions for improvement.

Keywords: thermospheric density; model error; error characteristics

1. Introduction

Although numerous studies have investigated thermospheric model performance, continuous evaluation throughout an entire solar cycle remains rare. This paper employs 2755 days of accelerometer-derived thermospheric density data from the CHAMP satellite (May 15, 2001 to December 31, 2008) to conduct statistical analysis of relative errors for the JB2008 and MSISE-00 models at 400 km altitude. Both atmospheric models generally overestimate density, but JB2008 significantly outperforms MSISE-00. Using the solar radiation index f10.7 and geomagnetic index Ap, we classified the space environment into four categories to characterize model errors under different conditions. Measured and modeled densities were analyzed by local time and latitude to compare model error characteristics across different local times, latitudes, and altitudes. This study contributes to refining our understanding of current thermospheric density model error characteristics and improvement directions.

Among current thermospheric atmospheric models, the most representative in terms of accuracy and application are the MSISE-00 model from the MSIS series, the JB2008 model from the Jacchia series, and the DTM-2013 model from the DTM series. As the DTM-2013 model was unavailable for this study, we evaluated only the first two models.

The MSISE-00 model, developed by Picone et al. at the U.S. Naval Research Laboratory (NRL), is an improved global atmospheric empirical model based on atmospheric total mass density data derived from satellite accelerometers and orbital data, molecular oxygen density data, and incoherent scatter radar temperature data. Building upon the MSISE90 model, it describes neutral atmospheric density, temperature, and other physical characteristics from the ground to the thermosphere (0–1000 km). As the latest version in the MSIS series, MSISE-00 uses the F10.7 index and its 81-day smoothed value to characterize solar activity effects, and daily and three-hourly Ap values to characterize geomagnetic disturbance effects. Due to its reasonable accuracy and readily available input parameters, it is widely used in aerospace engineering applications such as orbit prediction.

The JB2006 model was developed as part of the U.S. Air Force Space Command' s High Accuracy Satellite Drag Program. Its distinguishing feature is the adoption of solar radiation indices in the EUV and FUV bands and improved semi-annual density variation modeling. The Jacchia-Bowman 2008 (JB2008) model is an improved version of JB2006 based on the Jacchia diffusion equation. Data sources used in JB2008 development include daily density data from the U.S. Air Force (1997-2007), High Accuracy Satellite Drag Model (HASDM) data (2001-2005), CHAMP satellite accelerometer-derived density data (2001-2005), and GRACE satellite density data (2002-2005). Input space environment indices include solar indices F10.7, S10.7, M10.7, and Y10.7 calculated from on-orbit measurements. These indices characterize EUV to FUV solar radiation, including heating effects from X-ray and Lyman- bands. A new exospheric temperature equation was developed to respond to EUV and FUV heating, and a semi-annual density equation based on multiple 81-day averaged solar indices describes semi-annual density variations caused by EUV heating. Global density variations due to geomagnetic storms are characterized using the Dst index.

The DTM-2013 model was developed under the European Seventh Framework Program' s Advanced Thermosphere Modeling and Orbit Prediction project. It utilizes accelerometer-derived density data from CHAMP, GRACE, and GOCE; density data derived from Starlette and Stella laser ranging satellites; thermospheric temperature measurements from OGO-6; and mass spectrometer data from AE-C/E satellites. The model employs the 30 cm radio flux index f30 instead of f10.7, which better characterizes solar UV heating of the thermosphere and improves performance under low solar activity conditions. Geomagnetic effects use the Km index instead of the Kp index used in DTM-2009. Evaluation shows that except during the high solar activity period of 1999-2002 when JB2008 was superior, DTM-2013 outperforms both DTM-2009 and JB2008.

2. Data and Methodology

Using 2755 days of accelerometer-derived thermospheric density data from the CHAMP satellite (May 15, 2001 to December 31, 2008) as a benchmark, we performed statistical analysis of daily mean errors in the MSISE-00 and JB2008 models. Based on the simple and commonly used model inputs of solar radiation index f10.7 and geomagnetic index Ap, we classified the space environment into four categories as shown in Table 2 .

The relative error and standard deviation of the models were calculated as follows:

Where represents the model daily mean value, is the CHAMP satellite accelerometer-derived density daily mean, and is the mean relative error.

The mean relative errors and standard deviations of the two models under different space environment types exhibit distinct characteristics, as shown in Table 3 .

JB2008 shows smaller mean relative errors under environment types 00 and 01, while exhibiting mean relative errors of 10.37% and 4.42% under types 10 and 11, respectively, indicating overestimation of thermospheric density under these conditions. MSISE-00 shows a smaller mean relative error only under type 01, while displaying mean relative errors of 17.34%, 20.26%, and 12.92% under types 00, 10, and 11, respectively, indicating significant overestimation across these three environment types, particularly severe under type 10.

We statistically analyzed the relative errors of JB2008 and MSISE-00 at 400 km altitude. Figure 1 [Figure 1: see original paper] shows the relative error variation for both models at 400 km, demonstrating that JB2008 errors are substantially smaller than MSISE-00, with more stable errors during quiet solar periods. Additionally, MSISE-00 exhibits multiple cases of daily mean relative errors exceeding 100% during quiet space conditions, though the absolute errors remain relatively small due to low background density values, resulting in limited impact on space object orbit prediction and determination.

Figure 2 [Figure 2: see original paper] presents histograms of the relative error distribution intervals for both models at 400 km. JB2008 relative errors are predominantly distributed between -20% and 20%, while MSISE-00 shows a significant proportion (33.7%) of relative errors in the 20%-60% range. Table 4 provides detailed distribution intervals.

As shown in Table 4, JB2008 relative errors fall within the -20% to 20% range for 89.15% of cases, with a maximum daily mean positive error of 168.1% and maximum daily mean negative error of -38.3%. MSISE-00 relative errors in the -20% to 20% range account for 58.08% of cases, with a substantial proportion (23.81%) in the 20%-40% range. The maximum daily mean positive error reaches 240%, while the maximum daily mean negative error is -80%. In direct comparison of absolute daily mean relative errors, JB2008 outperforms MSISE-00 on 1958 days (71.1% of the total), while MSISE-00 performs better on 797 days (28.9%).

2.1 Height Characteristics

Comparisons with measured density reveal the daily mean density errors of JB2008 and MSISE-00 as functions of geomagnetic Ap, solar activity index f10.7, and altitude, as shown in Figure 3 [Figure 3: see original paper]. Analysis of Figures 3 and 4 [Figure 4: see original paper] yields the following conclusions:

(1) Below 450 km altitude, neither model exhibits clear height-dependent error characteristics, consistent with literature findings that both models overestimate thermospheric density below 500 km without significant height variation.

(2) Both models show pronounced f10.7 index dependence, with larger errors during moderate to high solar activity, particularly evident in MSISE-00.

Figure 4 shows the distribution of daily mean errors for JB2008 and MSISE-00 as functions of Ap and f10.7. The absolute error scatter plots reveal that JB2008 exhibits much smaller absolute errors than MSISE-00 during active f10.7 periods, benefiting from its use of new solar activity indices S10, M10, and Y10. During geomagnetically active periods, JB2008 also outperforms MSISE-00, attributable to its use of the Dst index. During the rising phase of f10.7 in solar maximum years, MSISE-00 shows exceptionally large errors that increase nearly linearly with f10.7, though no such relationship is observed with geomagnetic indices. The background trend of thermospheric density is consistent with f10.7 variations, while density jumps show strong correlation with Ap.

2.2 Latitude Characteristics

Using a 3° latitude bin width, Figure 5 [Figure 5: see original paper] presents the mean density from both models and measurements for the latitude range -87° to +87°. CHAMP measured density shows clear latitude characteristics with a distinct equatorial double-peak structure, reaching density minima near the northern hemisphere polar region that are lower than those in the southern hemisphere polar region. JB2008 demonstrates superior latitude characteristics compared to MSISE-00, with clearly defined peak-valley structures. Both models overestimate thermospheric density at all latitudes, with JB2008 showing severe overestimation at high latitudes and MSISE-00 severely overestimating across all latitudes.

Figure 6 [Figure 6: see original paper] shows the latitude characteristics of measured and modeled thermospheric density under the four space environment types (a–d corresponding to environment types 00, 01, 10, and 11). The results reveal that thermospheric density itself exhibits different latitude characteristics under different environments. For example, under geomagnetically disturbed type 01 conditions (Figure b), the equatorial region shows a single-peak structure, while the other three environment types (Figures a, c, d) display an equatorial double-peak structure with anomalously high polar region peaks caused by solar wind energy injection during magnetic disturbances.

MSISE-00 limitations: Except under type 01 disturbed conditions where it underestimates density at mid-low latitudes and overestimates at high latitudes, the model generally severely overestimates thermospheric density. MSISE-00 advantages: The latitude variation trend of density generally matches the measured density latitude variation.

JB2008 limitations: During solar activity disturbed periods (types 10 and 11), the model lacks latitude response and cannot represent thermospheric density variations with latitude, particularly evident at high latitudes. Except under type 00 conditions, JB2008 overestimates thermospheric density. JB2008 advantages: The model values are closer to measured values compared to MSISE-00.

2.3 Local Time Characteristics

We classified JB2008, MSISE-00, and CHAMP measured data (normalized to 400 km altitude) using a 1-hour local time bin width. Figure 7 [Figure 7: see original paper] shows the mean density values for models and measurements in the 0–24 hour interval. Both models exhibit different local time characteristics. CHAMP measured density shows clear local time variation, with density minima at 2–5h, followed by a steep increase, reaching maxima at 13–14h. Comparison with measured values reveals that JB2008 has poor overall local time response with indistinct density peaks and valleys, overestimating thermospheric density on the nightside and underestimating on the dayside. MSISE-00 demonstrates better local time response, capturing the density peaks and valleys, but overestimates at all local times.

Figure 8 [Figure 8: see original paper] presents the local time characteristics of measured and modeled thermospheric density under the four space environment types (a–d corresponding to types 00, 01, 10, and 11). Under type 00, 01, and 10 conditions, thermospheric density shows no significant peak-valley structural changes beyond amplitude variations. Under type 11 conditions, the density variation trend weakens across all local times, indicating that under combined solar and geomagnetic disturbances, thermospheric density approaches saturation and no longer responds significantly to local time. Across all four environment types, MSISE-00 shows good agreement with measured density, while JB2008 exhibits much poorer local time characteristics without clear peak-valley structures.

3. Summary

This study analyzed error characteristics of the current typical thermospheric models JB2008 and MSISE-00 using CHAMP satellite measured density data. We present overall and environment-specific error means and standard deviations, and characterize model errors by altitude, local time, and latitude. The main findings are summarized as follows:

Both models overestimate thermospheric density overall. JB2008 relative errors fall within the -20% to 20% range for 89.15% of cases, with maximum daily mean positive error of 168.1% and maximum daily mean negative error of -38.3%. MSISE-00 relative errors in the -20% to 20% range account for 58.08% of cases, with a substantial proportion (23.81%) in the 20%–40% range, maximum daily mean positive error of 240%, and maximum daily mean negative error of -80%. In direct comparison of absolute daily mean relative errors, JB2008 outperforms MSISE-00 on 1958 days (71.1% of the total), while MSISE-00 performs better on 797 days (28.9%). JB2008 shows smaller mean relative errors under environment types 00 and 01, while exhibiting mean relative errors of 10.37% and 4.42% under types 10 and 11, respectively, overestimating thermospheric density. MSISE-00 shows smaller mean relative error only under type 01, while displaying mean relative errors of 17.34%, 20.26%, and 12.92%

under types 00, 10, and 11, respectively, severely overestimating thermospheric density, particularly under type 10 conditions.

Measured density shows clear latitude characteristics with a distinct equatorial double-peak structure, reaching density minima near the northern hemisphere polar region that are lower than those in the southern hemisphere polar region. JB2008 demonstrates better latitude characteristics than MSISE-00 with clearly defined peak-valley structures. However, both models overestimate thermospheric density at all latitudes, with JB2008 showing severe overestimation at high latitudes and MSISE-00 severely overestimating across all latitudes.

Measured density exhibits clear local time characteristics, with density minima at 2–5h, followed by a steep increase, reaching maxima at 13–14h. JB2008 shows poor overall local time response with indistinct density peaks and valleys, overestimating thermospheric density on the nightside and underestimating on the dayside. MSISE-00 demonstrates better local time response, capturing the density peaks and valleys, but overestimates at all local times. Under type 00, 01, and 10 conditions, thermospheric density shows no significant 14h peak and 2h valley structural changes beyond amplitude variations. Under type 11 conditions, the overall local time density variation trend weakens; under combined solar and geomagnetic disturbances, thermospheric density approaches saturation and no longer shows clear response to local time. Across all four environment types, MSISE-00 shows good agreement with measured density, while JB2008 exhibits much poorer local time characteristics without clear peak-valley structures.

Future work should focus on detailed analysis of disturbance events with large model errors to characterize the latitude and local time dependencies of single-point model errors. This study provides valuable insights for refining our understanding of current thermospheric density model error characteristics and identifying directions for improvement.

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References

[1] WANG Hongbo, ZHAO Changyin. Validation of atmospheric model accuracy during solar maximum using CHAMP accelerometer data [J]. Acta Astronomica Sinica, 2008, 02): 168-78.

[2] PARDINI C, MOE K, ANSELMO L. Thermospheric density model biases at the 23rd sunspot maximum [J]. Planetary and Space Science, 2012, 67(1): 130-46.

[3] MURRAY S A, HENLEY E M, JACKSON D R, et al. Assessing the performance of thermospheric modeling with data assimilation throughout solar cycles 23 and 24 [J]. Space Weather-the International Journal of Research and Applications, 2015, 13(4):

[4] BRUINSMA S, TAMAGNAN D, BIANCALE R. Atmospheric densities derived from CHAMP/STAR accelerometer observations and neutral density models [J]. Planetary and Space Science, 2004, 52(4): 297-312.

[5] BOWMAN B R, TOBISKA W K, MARCO F A. A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices [J]. AIAA/AAS Astrodynamics Specialist Conference, 2008: 6438.

[6] BOWMAN B R, TOBISKA W K, MARCO F A. A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices [J]. 2008, 12): 6438: 2008.

[7] BRUINSMA S. The DTM-2013 thermosphere model [J]. Journal of Space Weather & Space Climate, 2015, 5(

[8] LIU Wei, WANG Ronglan, LIU Siqing, et al. Analysis of LEO prediction accuracy under four typical space environment conditions [J]. Journal of Astrodynamics, 2015, 5(3): 82-8.

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