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Key Points:

- SET HASDM density database is available for scientific studies
- Data covers solar cycles 23 and 24 with 3 h time steps from 175 to 825 km in 25 km altitude steps and 10 × 15° latitude, longitude bins
- SET HASDM database densities are suitable for use as a new space weather benchmark against which space weather events are measured

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The SET HASDM Density Database

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Abstract The SET HASDM density database is available for scientific studies through a SQL database with open community access. The information in the SET HASDM density database covers the period from January 1, 2000 through December 31, 2019. Data records exist every 3 h during solar cycles 23 and 24. The database has a grid size of 10° × 15° (latitude, longitude) with 25 km altitude steps between 175 and 825 km. A description of the source of the database, its validation, its information content, and its accessibility are provided.

Plain Language Summary The open community access SET HASDM density database is available for scientific studies. The database provides thermospheric densities covering the period from January 1, 2000 through December 31, 2019. Data records exist every 3 h during solar cycles 23 and 24. The database grid size is 10° latitude × 15° longitude with 25 km altitude steps between 175 and 825 km.

1. Current State of Art for Operational Thermospheric Densities

The United States Air Force (now United States Space Force, USSF) Combined Space Operations Center (CSpOC) creates arguably the world's most accurate current and forecast neutral thermosphere densities as part of their operation to produce the NORAD satellite catalog. To do this, they use the High Accuracy Satellite Drag Model (HASDM) v2 (Storz et al., 2005) as a data assimilative system working with its associated JB2008 model (Bowman et al., 2008; ISO 2013; Tobiska et al., 2008). HASDM continuously derives densities from several dozens of calibration satellites and revises the current epoch JB2008 densities using temperature correction coefficients to achieve very low global and regional density uncertainty at most epochs.

The JB2008 thermospheric density model (Bowman et al., 2008) was developed by the U.S. Air Force Space Command and Space Environment Technologies (SET) to improve current specification and forecast of thermospheric mass densities. Its creation led to the largest single reduction in thermospheric mass density uncertainties since the early Jacchia-type models in the 1960s (Marcos et al., 2006) where the 1-sigma uncertainties at 400 km for a given epoch dropped from 15% to 8% compared with previous Jacchia and MSIS models. The first improvement was to create new solar and geomagnetic indices that directly mapped solar irradiances from the Sun to the Earth's upper atmosphere. In addition to the legacy F10 solar proxy and the ap geomagnetic index, three new operational solar indices (S10, M10, andY10) were developed for JB2008 (Tobiska et al., 2008; ISO 2013) and the Dst geomagnetic index was incorporated as well.

The new solar indices represent the combined energy input from multiple solar sources: (a) S10 is the 26–34 nm bandpass EUV chromospheric irradiance index; (b) M10 is the 160 nm FUV Schumann-Runge photospheric irradiance proxy; and (c) Y10 is the 121.6 nm Lyman-alpha chromospheric/transition region irradiance convolved with the 0.1–0.8 nm X-ray coronal irradiance to create a new solar index. S10 represents the energy for O photoabsorption in the middle and upper thermosphere (>180 km), M10 represents the energy for O_2 dissociation in the lower thermosphere (~110 km), and Y10 represents the energy for mesosphere and lower thermosphere H_2O chemistry (~90 km). The F10 was retained for legacy use to account for unmodeled solar flux.

Geomagnetic storm and sub-storm representation was accomplished using the one-hour Dst index when it was less than −75 nT. Nonstorm, but unsettled, geomagnetic conditions continue to be modeled with the 3 h ap geomagnetic index, including during high-speed stream events. Forecast ap is operationally provided by NOAA SWPC and forecast Dst (Tobiska et al., 2013) plus the solar indices are operationally provided since 2012 by SET at https://sol.spacenvironment.net/JB2008/. Licata et al. (2020) have benchmarked the uncertainties in SET's solar and geomagnetic predictions.

JB2008 was adopted as part of the COSPAR International Reference Atmosphere (CIRA, 2014) and the ISO International Standard 14222 on Earth's upper atmosphere (ISO 2013), both of which recommend using JB2008 for calculating mass densities related to satellite drag. The densities are used in satellite orbit determination (OD) algorithms for Low Earth Orbit (LEO) to provide a solution for atmospheric drag.

The current epoch runs of the HASDM system during the course of an operational day at CSpOC are archived and contain the temperature-corrected coefficients that have been applied to the JB2008 atmosphere. The temperature corrected coefficients created at CSpOC are not released to the public. However, SET does validations of the HASDM output on a weekly basis to ensure the quality of the output product and is able to recreate the densities of the global atmosphere. This recreation is called the SET HASDM density database.

2. HASDM Validation

Satellite drag-derived atmospheric density variations depend upon the drag coefficient, C_D times the satellite frontal area, A, divided by mass, m. The inverse of this expression is also known as the ballistic coefficient, B. C_D is a function of satellite shape, thermospheric temperature, and thermospheric composition. Atmospheric winds cause variable velocity, v, affecting satellite drag variations at high latitudes during large geomagnetic storms. Legacy methods obtained density variations from analysis of satellite orbits using mean orbital elements or raw observational tracking data. Current methods analyze orbit decay rates using special orbit perturbations to fit satellite observations; however, those require very accurate radar availability and optical observations. The HASDM validation method uses densities derived from the use of special perturbations (SPs) OD employing daily orbital energy dissipation rates (EDRs) to obtain very accurate daily variations. Radar and optical observations from the worldwide USAF Space Surveillance Network (SSN) are used to fit precise orbital elements. A key element in this method is obtaining calibrated ballistic coefficients to compute the daily-observed density variations from the drag-derived computation (DDC) method using observed daily EDRs and differential orbit correction (DOC). Once these densities are determined for the calibration satellites, the least squares fitting assimilation of these calibration satellites' data into the JB2008 current epoch density solutions is then able to drop the HASDM density uncertainties to between 2–10% for a given epoch.

Validation of the overall HASDM system is done by SET. With the DDC method Bowman et al. (2004) uses government data sets and computes accurate daily thermospheric density values down to 150 km derived from SSN data. A SP DOC program fits SSN radar and optical observational data to obtain a standard 6-element state vector plus a ballistic coefficient, B. In this algorithm, the atmospheric density model used is the Modified Jacchia 1970 (Jacchia, 1971) model, i.e., J70Mod, developed originally for HASDM v1. EDRs are modeled over the observation span of 3–8 days using the J70Mod density values and the fitted B-value. Overlapping EDR values are used to compute accurate daily values. Daily temperature and density values are then calculated from the EDR using the average 30-year B-value of each satellite. The HASDM density model computes partial derivatives of temperature and EDR changes. The method was validated through comparison of daily temperature results during 2001 with the HASDM Dynamic Calibration Atmosphere (DCA) project. The comparisons were excellent and the computed daily densities were validated against historical daily densities for the last 30 years using many satellites. The density accuracy was quantified by comparing geographically overlapping perigee location data with over 8,500 pairs of density values used for the comparisons. The density errors are <4% overall and as low a 2% during the latest solar maximum.

The DOC method used to validate the HASDM orbital fit for individual orbiting objects incorporates a minimum of 10 accurate SSN radar observations spread throughout the fit span ensures accuracy; the majority use at least 30–60 observations per fit. The geopotential used in the DOC is the EGM96 model truncated to a 48×48 field. The use of the 48×48 field results in maximum B errors <4% with a standard deviation <1% for an orbit with a perigee height close to 400 km. These are acceptable to obtain the desired density accuracy. The SP integration includes third-body gravitational effects of the Sun and Moon, solar radiation pressure, and atmospheric drag accelerations. A variable C_D is required for the processing.

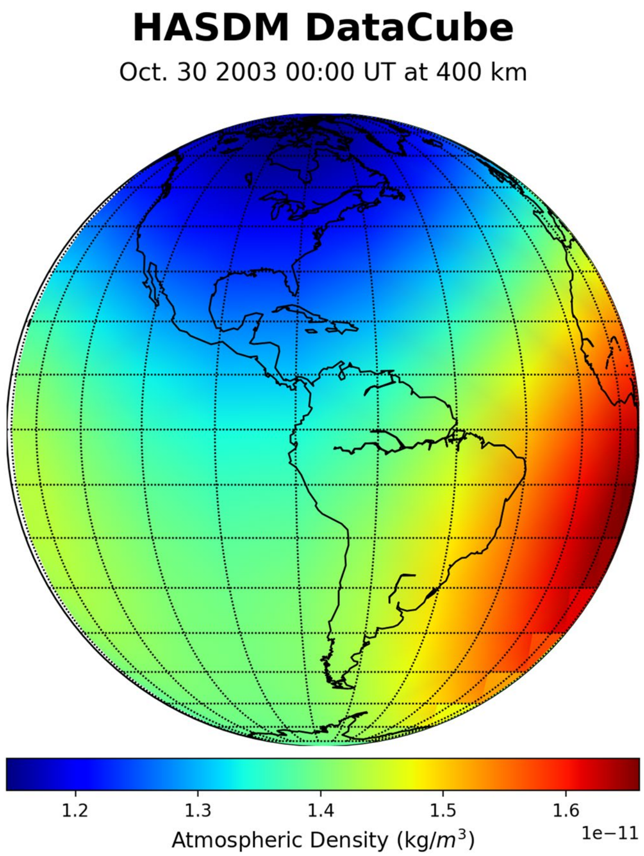

Figure 1. The SET HASDM database example shown for the Halloween storm period of 2003.

A final step in the HASDM validation uses the EDR to compute accurate daily density values for an orbiting object. DOC was first modified to compute orbital EDR over an observation span using J70Mod density and fitted *B* values (Bowman & Hrncir, 2007). Overlapping EDR values are obtained by moving the observation span by one day and then recomputing another orbit fit with the same span length. Overlapping fits are then used to compute accurate daily EDR values using a weighting method favoring EDR values obtained from the middle of the observation span as opposed to those at the ends of the span. Finally, daily EDR values are used to compute observed daily temperature values. The daily EDR values are obtained from averaging the same day's overlapping values obtained from the orbit fits. Because of fit error, the best method for obtaining an accurate daily EDR is to constrain the average daily EDR to maintain conservation of energy over each orbit fit span. Thus, energy change over each fit must be preserved since these were the real measured quantities when the orbit fits were obtained.

3. SET HASDM Density Database Extraction and Availability

Under authority from USSF, SET has extracted two solar cycles of temperature-corrected coefficients and created the SET HASDM density database. This is the first-time there has been an extraction of this operational database for scientific use; there is no comparable data set in existence. All solar cycle, geomagnetic storm and sub-storm, extended solar flare, and thermospheric cooling perturbations are embedded in the data. Because of its accuracy, time resolution, global scale, and information content, the SET HASDM database densities are suitable for use as a new space weather benchmark for atmospheric expansion against which space weather events are measured. A new benchmark refines the Phase 1 Benchmark that was released by the National Science and Technology Council (SWAP, 2019) for upper atmospheric expansion.

The statistical metrics in the SET HASDM density database are being characterized by the META-HASDM project which uses machine learning to quantify the database. That work is being developed separately for publication. Called HASDM ML, it will characterize the global density environment for rapid operational use, for quantification of uncertainty, and for improving ballistic coefficients for all LEO objects.

The SET HASDM density database now resides in a SQL database with open community access for scientific studies. The information in the SQL SET HASDM density database, with an example in Figure 1 for the Halloween 2003 storm period, covers the period from January 1, 2000 through December 31, 2019. Data records exist every 3 h during solar cycles 23 and 24. The database has a grid size of 10° × 15° (latitude, longitude) with 25 km altitude steps between 175 and 825 km.

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Data Availability Statement

The database access, along with supplementary information, can be found at https://spacewx.com/hasdm/.

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