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A TRADE STUDY OF THERMOSPHERE EMPIRICAL NEUTRAL DENSITY MODELS

Chin S. Lin, et al.

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Final Report

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14. ABSTRACT
Accurate orbit prediction of space objects critically relies on modeling of thermospheric neutral density that determines drag force. In a trade study we have investigated a methodology to assess performances of neutral density models in predicting orbit against a baseline orbit trajectory. We use a metric defined as along-track error in a day a satellite is predicted to have for a given neutral density model when compared to its GPS positions. A set of ground truth data including Gravity Recovery and Climate Experiment (GRACE) accelerometer and GPS data, solar radio F10.7 proxy and magnetic activity measurements are used to calculate the baseline orbit. This approach is applied to compare the daily along-track errors among HASDM, JB08, MSISE-00 and DTM-2012 neutral density models. The dynamically calibrated HASDM model yields a daily along-track error close to the baseline error and lower than the other empirical models. Among the three empirical models (JB08, MSISE-00 and DTM-2012) the MSISE-00 model has produced the smallest daily along-track error. The results suggest that the developed metric and methodology could be used to assess overall errors in orbit prediction expected from empirical density models. They have also been adapted in an analysis tool Satellite Orbital Drag Error Estimator (SODEE) to estimate orbit prediction errors.

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1. INTRODUCTION

Accurate orbit prediction of space objects critically relies on modeling of thermospheric neutral density that determines drag force. In this trade study we present a methodology to assess performances of empirical neutral density models in predicting orbit against a "ground truth" orbit trajectory. We have evaluated the overall along-track error of predicting Gravity Recovery and Climate Experiment (GRACE) satellite orbit using three empirical models including the Committee on Space Research (COSPAR) reference models MSISE-00 [Picone et al, 2002] and the Jacchia-Bowman 2008 model (JB08), and the recently updated Drag Temperature Model (DTM) developed by a European Union 7th framework project. Our approach is to calculate along-track errors for these models and compare them against the baseline error based on the "ground truth" neutral density data measured by the GRACE satellite onboard accelerometer. In addition we want to evaluate their performances against another orbit tracking benchmark based on the Air Force neutral density operational model - High Accuracy Satellite Drag Model (HASDM) [Storz et al., 2002]. The purpose of the trade study is to assess the current state-of-the art of orbit prediction.

Atmospheric drag is the dominant error source in force models used to predict low altitude satellite trajectories. Atmospheric density models are required in computing the atmospheric drag force in satellite orbit determination and prediction. If at satellite altitudes an atmospheric neutral density model does not adequately account for dynamic changes in neutral density, significant errors occur in predicted satellite positions. The Air Force has developed a High Accuracy Satellite Drag Model program that computes "real time" upper atmospheric neutral density variations using 75-80 calibration satellites in a wide range of orbit inclinations and perigee heights ranging from 200 *km* to 800 *km*. The HASDM program estimates a set of density correction parameters every 3 hours, which describe density as a function of latitude, local solar time, and altitude. A time series filter then predicts (out three days) the density correction parameters as a function of predicted solar radio flux index $F_{10.7}$ and predicted geomagnetic storm index a_p. The estimated and predicted density fields are used to first differentially correct all the drag influenced orbits (over 8,000) in the NORAD catalog, and then predict all satellite trajectories out three days. This tool is extremely important for maintaining object custody at low earth orbit (LEO) and has continued to evolve since its first inspection in the early 2000's.

Empirical models (MSISE-00, JB08, DTM, and others) are particularly limited in their capability to respond to the highly variable solar and geomagnetic variations. They are parameterized in terms of mainly proxy geophysical indices that are daily, 3-hourly, and hourly at their highest resolution, and so are not suited to track hour-to-hour variations. Furthermore, being based on data, they are limited when extrapolating beyond the range of data. For example, the Jacchia-Bowman 2008 (JB08) model errors for large storms are ~27% for point measurements. Using orbit averages for selected storms Bowman et al. [2008] showed that the smoothing reduced errors to ~13%.

Several studies have statistically evaluated the above-listed models by comparing their model densities with high resolution total neutral density data inferred from CHAMP [Reigber et al., 2002] and GRACE [Tapley et al., 2004] accelerometer measurements since 2001 [notably Bowman et al. 2008; Bruinsma et al. 2012]. These previous studies generally used mean and root-square-error (RMSE) as metrics. In the present study we use a different metric – the daily along-track error in a day a satellite is expected to have for a given density model. Not only providing a different perspective on the model performances, this metric provides an advantage of directly relating the model density error to its overall impacts on orbit determination. Such a trade study using the along-track error metric has not been attempted before.

The next section summarizes the methods and procedures used to calculate the metric. In Section 3 we present the ground-truth neutral density dataset including that from the HASDM model. The empirical density models are described in Section 4. Section 5 contains the trade study results and discussion. Concluding remarks are presented in Section 6.

2. METHODS, ASSUMPTIONS, AND PROCEDURES

At low earth orbit, the dominant perturbing force beside gravitation force is the drag force. Solar radiation pressure and tidal force, and other non-conservative forces are much smaller. The equations of motion of a satellite can be written as

$$\ddot{\vec{r}} = \vec{\nabla} V + \vec{a}_D \tag{1}$$

where $\vec{r}$ is the position vector, V is the gravitational potential function and $\vec{a}_D$ is the satellite drag deceleration vector. We have neglected perturbing forces due to solar radiation pressure and tides. As explained in Vallado [2013] (see Figures 9-16 and 9-17), effects of solar radiation pressure and tides on orbit are at least two orders of magnitude smaller than the drag force at LEO altitudes less than 500 *km*.

We represent the gravitational potential V by using the Earth Gravitational Model 1996 (EGM96) developed by the NASA Goddard Space Flight Center (GSFC), the National Imagery and Mapping Agency (NIMA), and the Ohio State University (OSU) [Lemoine et al., 1998]. In the EGM96 model the gravitational potential function V is defined as

$$V = \frac{GM}{r}\left[1 + \sum_{n=2}^{n_{max}} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n \bar{P}_{nm}(\sin\phi')(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\right] \tag{2}$$

where:

V = Gravitational potential function (m^2/s^2)

GM = Earth's gravitational constant

r = Distance from the Earth's center of mass

a = Semi-major axis of the WGS 84 ellipsoid

n,m = Degree and order, respectively

ϕ' = Geocentric latitude

λ = Geocentric longitude

$\bar{C}_{nm}$, $\bar{S}_{nm}$ = Normalized gravitational coefficients

$\bar{P}_{nm}(\sin\phi')$ = Normalized associated Legendre function

$$= \left[\frac{(n-m)!(2n+1)k}{(n+m)!} P_{nm}(\sin\phi')\right]^{1/2}$$

$P_{nm}(\sin\phi')$ = Associated Legendre function

$$= (\cos\phi')^m \frac{d^n}{d(\sin\phi')^m} [P_n(\sin\phi')]$$

$P_n(\sin\phi')$ = Legendre polynomial

$$= \frac{1}{2^n n!} \frac{d^n}{d(\sin\phi')^n} (\sin^2\phi' - 1)^n$$

Note: The $\bar{C}_{nm}$ and $\bar{S}_{nm}$ coefficients are given in the EGM96 model. For $m = 0$, k equals to 1, and for $m \neq 0$, k = 2.

The complete EGM96 model is a spherical expansion of the gravitation potential function V through degree (*n*) and order (*m*) 360. We use $n \leq 70$ and $m \leq 70$ for gravitational force calculations in accordance with recommendations from the National Imagery and Mapping Agency (NIMA) Technical Report 8350.2 for purposes of high accuracy satellite orbit determination and prediction. The EGM96 through degree and order 70 will produce position error below 100 meter after one day of orbit propagation at 500 *km* altitude (see Figure 9-17 of Vallado [2013]).

Aerodynamic drag deceleration $\vec{a}_D$ depends on neutral density ρ, as well as satellite area-to-mass ratio, drag coefficient C_D, and the velocity of the satellite with respect to the surrounding atmosphere $\vec{v}$ as:

$$\vec{a}_D = -\frac{1}{2}\left(\frac{C_D A_{ref}}{m}\right)\rho|\vec{v}|\vec{v} \tag{3}$$

where A_{ref} is the reference satellite area projected into the ram direction, and *m* is the satellite mass. The velocity $\vec{v}$ equals to the satellite velocity in the corotating Earth frame $\vec{v}_c$ minus the ambient neutral wind speed $\vec{w}_c$ such that $\vec{v} = \vec{v}_c - \vec{w}_c$. Because neutral wind velocity is generally of the order of 100 *m/s* thus much smaller than spacecraft velocity (~ 7.5 *km/s*), we have omitted neutral wind effects. Furthermore we treat both the satellite area/mass ratio A_{ref}/m and drag coefficient C_D constant along the orbit. The parameters we use are A = 1.15 m^2, m = 475 *kg*, and C_D = 3 for the GRACE satellite.

To propagate the orbit we integrate Eq. (1) from the initial time of an epoch ($t = 0$) to time *t* in the Earth centered inertial (ECI) coordinate. The ECI coordinate system also known as the geocentric equatorial system has the origin at the center of the Earth and three axes designated as *I, J,* and *K* (See Vallado [2013] for description and discussion). The *I* axis points towards the vernal equinox, the *J* axis is 90^o to the east in the equatorial plane, and the *K* axis is the axis of rotation. We rewrite Eq. (1) into a system of six first-order differential equations using the three-component position (*x, y, z*) and velocity (*dx/dt, dy/dt, dz/dt*) vectors. We define a vector $\vec{X}$ as

$$\vec{X} = \begin{bmatrix} \vec{r} \\ \vec{v} \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ dx/dt \\ dy/dt \\ dz/dt \end{bmatrix} \tag{4}$$

The system of equations then becomes

$$\dot{\vec{X}} = \begin{bmatrix} \vec{v} \\ \vec{\nabla} V + \vec{a}_D \end{bmatrix} \tag{5}$$

We used the fourth-order Runge-Kutta method with a fixed time step of 10 seconds for numerical integration. The EGM96 model specifies *V* in the Earth-Center, Earth-Fixed (ECEF) coordinate frame, a geocentric coordinate system fixed to the rotating Earth [Vallado, 2013]. To compute $\vec{\nabla} V$ at position $\vec{X}$ we first transform ECI position $\vec{X}$ to the ECEF coordinate at every intermediate time steps before calling the EGM96 model. After taking the derivative of *V* in the ECEF coordinate we then transform $\vec{\nabla} V$ back to the ECI coordinate system. The transformations between the ECI and ECEF coordinates have been treated in great details with algorithms and examples by Vallado [2013]. We therefore will not repeat its description here.

Metric

The metric is calculated as the daily along-track error ε a satellite is predicted to have for a given neutral density model with respect to the satellite GPS positions $\vec{r}_{GPS}$ at the end of the day. The daily along-track error ε can be expressed as:

$$\varepsilon = \left(\vec{r}_p - \vec{r}_{GPS} \right) \cdot \vec{v}_{GPS} \tag{6}$$

where $\vec{r}_p$ is the predicted position at the end of day, $\vec{r}_{GPS}$ and $\vec{v}_{GPS}$ are the satellite actual position and velocity vectors at the end of day measured by its onboard GPS sensor, respectively. Because GPS position and velocity measurements are used to start the orbit propagation at the beginning of each day, the initial along-track error ε(*t=0*) is zero. The predicted position $\vec{r}_p(\mathrm{t} = 86400\ s)$ is obtained by numerically integrating Eq. (5) with a fixed time step of 10 seconds.

We have calculated GRACE's daily along-track error ε_G for 2011 using its GPS positions and velocities determined from data files from the NASA GRACE Data center, which provides GPS data from the beginning of the day at every minute interval. The inferred GRACE neutral density data is used in calculating ε_G. Similarly the model error ε_M was calculated for four neutral density models (the subscript M stands for HASDM, MSIS, JB08, or DTM) using the same initial position and velocity. The only difference between ε_G and ε_M is that the ε_G calculation uses the ground truth density inferred from satellite accelerometer whereas the ε_M calculation uses the model density. The absolute value of ε_G is regarded as the baseline error.

3. GROUND TRUTH NEUTRAL DENSITY DATASET

Sutton [2009] has built a dataset of the total neutral density along the GRACE orbit for the period starting from the launch using its accelerometer measurements. In this study we used the currently updated version 2.3 of the dataset [Sutton, 2011]. GRACE with a twin satellite configuration was launched on March 17, 2002 into an almost circular, near-polar orbit (inclination 89.0°) with an initial altitude of 500 *km*. Because the primary mission objective of the GRACE satellite is to map the global gravity field with unprecedented accuracy, GRACE carries extremely sensitive SuperSTAR accelerometers. The accelerometers onboard these satellites measure the vector quantity of acceleration caused by nongravitational forces. After modeling and removal of the acceleration signals caused by solar radiation, Earth's albedo and infrared radiation, Sutton [2009] derived the total neutral density.

Due to the need to reduce the size of the density dataset without degrading the quality, the data has been binned and averaged along the satellite's orbit in 3-degree latitudinal increments. The bins are centered around the latitude that steps from -90^o to 90^o by 3-degree size. When there are no data points in the averaging bin, the data bins are omitted. The average time duration of the data bin is 47 second. Figure 1 shows a typical example of neutral density variation (blue curve in the top panel) along the GRACE orbit in day 150, 2011. Neutral density oscillates periodically from orbit to orbit within an envelope from the minimum at the apogee to the maximum at the perigee. The orbital latitude and altitude are shown in the third and bottom panels, respectively. Since GRACE is in a near-polar orbit, the longitude is almost constant over the course of half of an orbit, and is therefore not shown. The density varies basically in sync with altitude such that higher density is detected at lower altitude. In addition to the satellite's height density typically varies with the satellite's local time over the course of an orbit. In this particular case, GRACE's local time variations just happen to be in phase with its height variations

For comparison we display the HASDM model density (red curve) along the GRACE satellite trajectory in the top panel of Figure 1 as well. It follows closely with the GRACE density (blue curve). The ratio of HASDM over GRACE density shown in the second panel has a mean value about 1.1 and a standard deviation around 0.05.

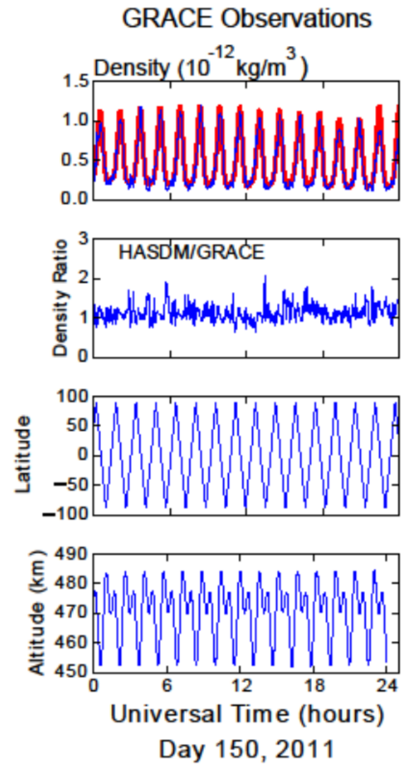

Figure 1. Neutral density variation measured in day 150, 2011. *The top panel displays the GRACE density in blue and the HASDM model density in red. The ratio of HASDM model density over the GRACE density is plotted in the second panel. The third and fourth panels display latitude and altitude along the GRACE orbit, respectively.*

Figure 2 illustrates the accumulation of the along-track error $\varepsilon(t)$ as a function of time. In this case $\varepsilon(t)$ was calculated relative to the GPS position at every minute from the beginning of day 150, 2011. With the GRACE measured density $\varepsilon(t)$ increases linearly with time from zero to about 300 *m* at the end of day (blue curve). However when the HASDM density model is used instead, $\varepsilon(t)$ increases at a faster rate (red curve), reaching close to 400 *m* at the end of the day.

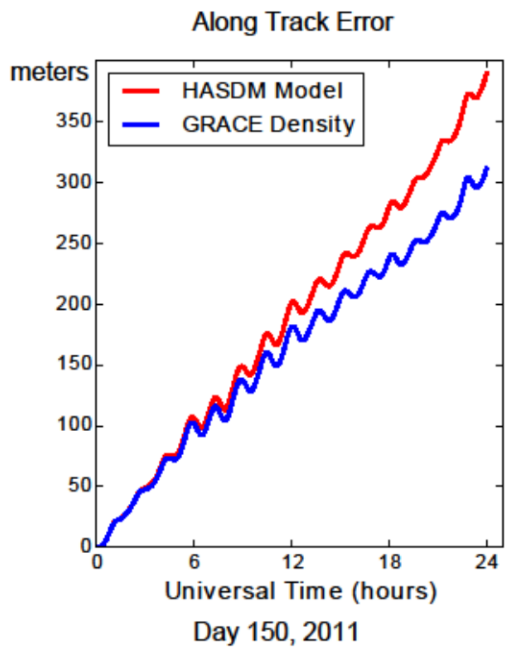

Figure 2. Accumulation of along-track error with time for day 150, 2011 for the GRACE measured density (blue curve) and the HASDM model density (red curve).

Neutral density values from the HASDM model are used operationally by AFSPC to catalog satellite and space debris. They are often considered as a bench mark for neutral density modeling. The "ground-truth" quality of the HASDM is derived from its "real time" global neutral density variations based on extensive satellite tracking observations of 75-100 calibration satellites in a wide range of orbit inclinations and perigee heights. Drag information deduced from the trajectories of calibration satellites is used to solve a dynamically changing global correction to the thermosphere density and temperature profiles in the altitude range of ~200 to 800 *km*. The HASDM program estimates a set of atmospheric temperature correction parameters every 3 hours, which are applied to describe density as a function of latitude, local solar time, and altitude. However along the GRACE orbit the HASDM temporal and spatial resolutions do not match in fidelity as those inferred from the in-situ accelerometers.

4. EMPIRICAL NEUTRAL DENSITY MODELS

Various empirical atmospheric neutral density models have been used in orbit trajectory calculation. In this section we describe three well-known models: MSISE-00, JB08, and DTM.

MSISE-00 (Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended Model)

The MSISE-00 empirical atmosphere model, developed by Picone et al. [2002], is based on a very large set of observation data from satellites, rockets, and radars. It is upgraded from its previous versions with assimilation of total mass density values determined from drag on satellites and other space objects. Employing solar flux F10.7 proxy and the geomagnetic activity a_p index it models the neutral temperature and densities in Earth's atmosphere from ground to above the thermosphere (~1000 *km*). It is considered as the standard for international space research, and often employed to help predict satellite orbit.

JB08 Model

The recently upgraded Jacchia-Bowman 2008 (JB08) model has been reported to achieve significant improvements in empirical density modeling [Bowman et al., 2008]. The upgrade has incorporated new solar indices, a new semiannual variation equation, and a new geomagnetic index. In addition to the standard solar flux irradiation F10.7 proxy, the JB08 uses three additional driving solar indices to represent solar irradiances in the extreme through far ultraviolet, including x-ray and Lyman-α wavelengths. Geomagnetic storm effects on thermosphere heating are modeled by using either the 1-hour Dst Index during major geomagnetic storms and substorms or the 3-hour a_p geomagnetic index during less magnetically active conditions (Dst < 75). The JB08 has been validated by applying neutral density data from the CHAMP and GRACE satellites. It was also validated through comparisons with accurate daily density drag data deduced from numerous satellites in the altitude range of 175 to 1000 *km*. Comparisons with the earlier models including JB2006, Jacchia 1970, and MSISE-00 indicate that the JB08 has performed very well [Bowman et al., 2008]. It provides standard deviations of approximately 9-10% at 400 *km*, a significant decrease from 16% previously obtained using the Jacchia 70 model, which is the base model in the HASDM. The JB08 modeling altitude is limited from 120 *km* at the upper atmosphere to 2500 *km* in the exosphere.

DTM Model

The Drag Temperature Model (DTM) is a semi-empirical model describing the temperature, density and composition of the Earth's thermosphere between an altitude of 120 *km* to approximately 1500 *km*. The exospheric temperature and the total density variations are modeled as a function of environmental parameters including latitude, local solar time, and geomagnetic activity. The DTM is developed and maintained by Centre national d'études spatiales (CNES) of France since 1978 with various upgrades. The recent versions since 2009 have been upgraded with assimilation of high-accuracy and high-resolution densities inferred from accelerometers onboard CHAMP [Bruinsma et al., 2004] and GRACE [Tapley et al., 2004]. The DTM-2009 version has been evaluated and compared with several well-known empirical density models (MSISE-00, JB08, and earlier DTM version DTM-2000). It is found to be significantly improved over these previous empirical models and has overall high fidelity for modeling thermosphere density [Bruinsma et al., 2012]. We used the 2012 version in this study.

The DTM model requires four input arguments: latitude, longitude, altitude and date. It uses the 1-day delayed solar radio flux at 10.7 *cm* and its 81-day mean as the solar indices, and the planetary geomagnetic index Km instead of the popular index Kp as the geomagnetic activity index. The Km index is derived similarly to Kp except that it is based on the subauroral stations evenly spaced in longitude at the corrected geomagnetic latitudes below 59^o. The solar and Km indices are provided by the International Service of Geomagnetic Indices/LATMOS, Institute de Research en Sciences de l'environnement, France, available from its website *http://isgi.latmos.ipsl.fr/.*

5. RESULTS AND DISCUSSION

We present the orbit-averaged neutral density inferred from GRACE accelerometer measurements for 2011 in Figure 3 (blue line, top panel). There were two intervals of data gaps around day180 and day 350. The inferred density corresponded to the F10.7 proxy variation (second panel). From the beginning of the year till day 250, F10.7 varied around 100 exhibiting low and moderate UV radiation, which apparently resulted in low orbit averaged density less than 10^{-12} kg/m^3. After day 250 the F10.7 proxy increased from 100 to an average of about 150. This was apparently correlated with a steady increase in the orbit-averaged density to over $2x10^{-12}$ kg/m^3. The envelope of density variation in an orbit expanded too as seen by the range between the minimum density (black line) and the maximum density (red line) in an orbit. The orbital maximum density was more variable and had reached above $5x10^{-12}$ kg/m^3, while the orbital minimum density varied gradually.

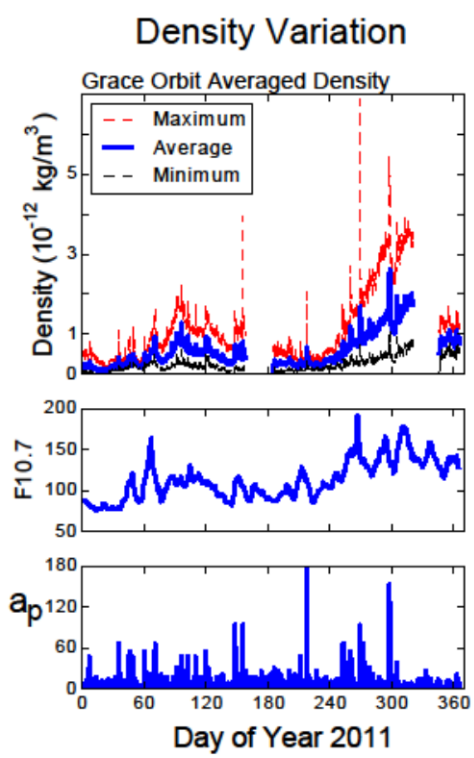

Figure 3. Orbit averaged density in correlation with F10.7 proxy and a_p index for 2011. *The orbit averaged density is plotted as the blue line with the orbital maximum density as the red line and the orbital minimum density as the black line in the top panel. The F0.7 proxy is shown in the second panel, and the a_p index in the bottom panel.*

The 3-hourly a_p index indicates that magnetic activity was low through 2011 (bottom panel). Several moderate magnetic storms occurred around days 205 and 298. Distinctly visible were large density spikes associated with these magnetic storms.

Figure 4 shows the orbit averaged ratios of model density over the GRACE measured density for four models (HASDM, MSISE-00, JB08 and DTM-2012) for 2011. Ratios in the interval from day 5 to day 28 are excluded in the plot because an unresolved calibration problem yielded bad density data points near the apogee. As expected the HASDM model density is uniformly close to the GRACE measurements (yellow line). The mean value of the HASDM/GRACE ratio is only 1.12. The JB08/GRACE density ratio is overall less than 1 with a mean value around 0.9 (red line). The MSISE-00/GRACE ratio contrasts with a value typically greater than 1 (green line). Its mean value is 1.29. The DTM-2012/GRACE density ratio has a mean value of 1.12 but with a large standard deviation (blue line). The density ratio reflects how much its corresponding model affects satellite drag error, which in turn determines its effects on trajectory prediction accuracy. The mean value is especially crucial for determining track position error because the resulting error accumulates.

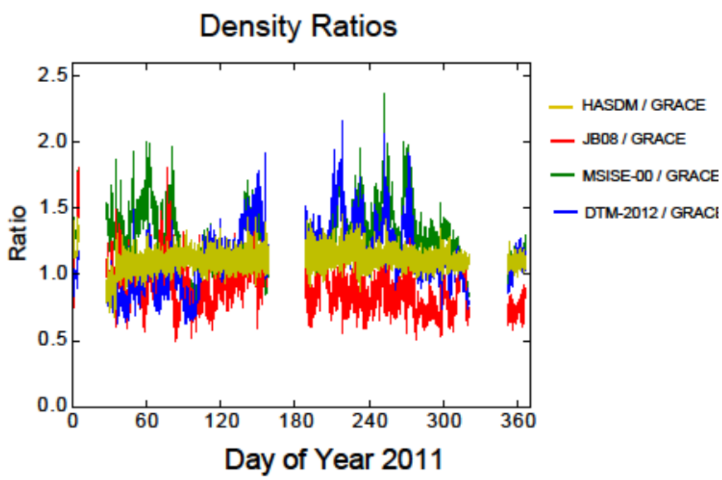

Figure 4. Ratios of model density over the GRACE measured density for four models (HASDM, MSISE-00, JB08 and DTM-2012) for 2011. *The ratios are averaged over orbit with a time resolution of 90 minutes. The HASDM/GRACE density ratio is plotted in yellow, the JB08/GRACE in red, MSISE-00/GRACE in green, and DTM-2012/GRACE in blue.*

Figure 5 shows the daily along-track error ε as defined in Equation (6) and described in Section 2 on the metric. Recall that ε is computed by first integrating GRACE trajectory based on a given density model from the beginning of a day to the end of the day and then calculating the difference between the predicted position and the satellite GPS position. In order to compare performance of a density model with ground truth data, we compute the model density only at GRACE satellite positions where neutral density data were available. Generally the average time step between successive GRACE density data points is around 47 seconds. The top panel compares two ground truth daily track errors, the baseline error ε_G (red line) based on the GRACE neutral density data and ε_{HASDM} deduced from the HASDM model (blue line). The baseline error ε_G is less than 200 *m* before day 250 and increases to about 400 *m* during days 300 - 330. The ε_{HASDM} stays around 200 *m* through the whole year, comparable to ε_G before day 250 and lower than ε_G during days 300 – 330. The ε_{HASDM} is expected to be low because HASDM model has used calibration satellite tracking to correct its global density modeling.

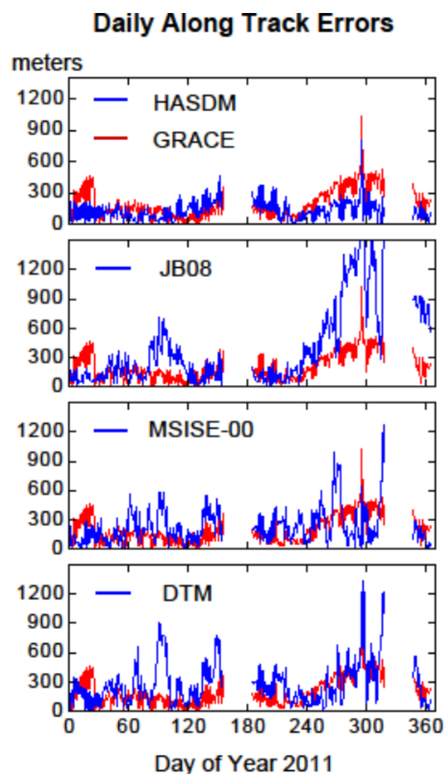

Figure 5. Empirical model daily along-track errors for 2011. *From top to bottom each panel plots in sequence daily along-track errors for HASDM, JB08, MSISE-00 and DTM-2012. The baseline error* ε_G *is plotted as red line in each panel.*

The JB08 model along-track error ε_{JB08} is generally larger than ε_G (second panel). The error is quite large reaching as high as 1500 *m* during days 250 – 320 when F10.7 was elevated.

The MSISE-00 model daily along-track error ε_{MSIS} is also mostly larger than ε_G (third panel). It varies between 100 to 600 *m* during magnetic activity quiet period (before day 240). The ε_{MSIS} reaches 800 *m* for a few days around day 270 during a moderate magnetic storm when a_p index had a small peak ($a_p \sim 80$). The MSISE-00 model appears to perform better than the JB08 model.

The DTM-2012 model daily along-track error ε_{DTM} varies from 100 *m* to 800 *m* in the period before day 270 (fourth panel), which is usually larger than ε_G. During this magnetic quiet period ε_{DTM} is slightly higher than ε_{MSIS} (third panel). It indicates larger errors about 1200 *m* for a few days before day 300 in association with magnetic activity, but overall ε_{DTM} behaves better than ε_{JB08} (second panel) during magnetic disturbances.

Figure 6 indicates that ε_G was systematically larger than ε_{HASDM} during days 240 - 330 (top panel). This might indicate that the inferred density in this period had a systematic bias. There are several plausible reasons that can cause this. One reason is that the accelerometer measurements recorded onboard GRACE might retain large error due to uncertainty associated with the process of accelerometer calibration. The accelerometers are insensitive to long-period accelerations, and must be calibrated via GPS. Calculation of ε_G might yield a larger than normal error if the time series of density had a calibration bias. Another possible reason might be that the satellite area/mass ratio A_{ref}/m and drag coefficient C_D constants used in this study were inaccurate, with the error varying in time due to satellite orientation, change in mass due to thrusts, and/or neutral composition effects on C_D.

We average the daily along-track error ratios over 2011 and present the statistics in Figure 6. The HASDM model has the lowest averaged ratio $<\varepsilon_{HASDM}/\varepsilon_G>$ around 1.1 with a standard deviation of 1.4, where the bracket <> denotes the yearly average. The MSISE-00 model has the second best performance with $<\varepsilon_{MSIS}/\varepsilon_G> = 2.1$ and a standard deviation of 2.4. The DTM-2012 model comes in the third with a mean ratio of 2.4 for $<\varepsilon_{DTM}/\varepsilon_G>$ and a standard deviation of 2.7. The JB08 model performed worst with a mean value of 2.7 for $<\varepsilon_{JB08}/\varepsilon_G>$ and a standard deviation of 3.5. Its poor performance is attributed to large ε_{JB08} during periods of high a_p values in days 270 -330 (see third panel, Figure 5).

It is sensible that $<\varepsilon_{HASDM}/\varepsilon_G>$ is much lower than the other models since the HASDM model has dynamically corrected its density modeling with real time orbit tracking data. Among the three empirical models (JB08, MSISE-00 and DTM-2012) our results indicate that the MSISE-00 model has the smallest daily along-track error and the JB08 model has the largest error.

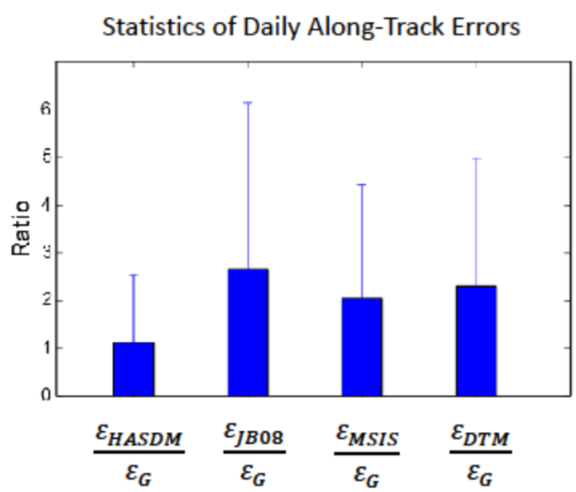

Figure 6. Statistics of the daily along-track error ratios.

Bruinsma et al. [2012] demonstrated that JB08 is most accurate for altitudes below 400 *km*, whereas DTM and MSISE-00 are clearly more accurate for altitudes above 500 *km*. Our results based on orbit prediction around 500 *km* are consistent with Bruinsma et al. [2012]. Degradation of the JB08 model with altitude is in large part due to the simple description of neutral composition employed by the model, the effect of which becomes increasingly significant with altitude. Another reason might be that this trade study was conducted for 2011 when the past solar minimum was still nearing the end. The recent solar minimum has shown errors of 50% in density model estimation because the F10.7– EUV one-to-one relation did not hold. JB08, while using measurements as part of the EUV input, is still heavily weighted in favor of the F10 index. In fact the model has an ad hoc correction that arbitrarily represents density variability with decreasing solar flux in order to better match historical data. This might contribute partially to large $<\varepsilon_{JB08}/\varepsilon_G>$.

The along-track error follows closely with satellite drag uncertainty due to neutral density variability. For example, the baseline error ε_G appears to be large in days 270 - 330 during period of secular increase in density variability and F10.7 (Figure 3). Another secondary factor contributing to the baseline error ε_G is the number of data gaps per day. In order to compare the performance of empirical models with the ground truth, we have calculated the model along-track errors at the same time and locations as GRACE density data points, rather than calculating them at finer resolution. Therefore the model along-track error ε_M calculation is also affected by the number of GRACE data points used. For data quality control we discarded some accelerometer measurements, resulting in data gaps and a larger time step between data points. The orbit error tends to be larger for days in which a high fraction of the GRACE density data bins are missing. Increasing the number of neutral density data points by decreasing time step size will help reduce the along-track error.

This report describes our first attempt to develop a methodology for comparing performances of empirical models. We have focused on total mass density variations and utilized the same input variables for all models. It should be pointed out that in addition to neutral density satellite drag error may be contributed by other factors including errors and approximations in the satellite macro models, the drag coefficients, and surface-to-mass ratios used in their derivation. These factors are treated as unchanged when computing trajectory error.

6. CONCLUSIONS

Neutral density forecasting is a critical factor for LEO object orbit prediction. Accurate specification and prediction of neutral density variations is necessary to calculate satellite drag and orbital trajectories precisely needed for satellite reentry predictions, timely collision avoidance warnings, and catalog maintenance of all space objects. In this trade study we present a methodology to assess performance of neutral density models in predicting orbit against the baseline orbit calculated from the accelerometer neutral density and GPS position data of the GRACE satellite. The metric used is satellite's daily along-track error when compared to its GPS positions.

We apply this approach to compare the overall along-track errors of HASDM, JB08, MSISE-00 and DTM-2012 models. As expected the dynamically calibrated HASDM model produces the lowest daily along-track error. Our results indicate that the MSISE-00 model has yielded a smaller daily along-track error than the other two empirical models.

Performance of empirical models depends on altitude, solar cycle and possibly other factors. We caution that our comparison of empirical models is based only on one year of GRACE accelerometer data and its performance evaluation may not be generalized yet without more extensive analysis using other datasets. Empirical models are known to be particularly limited in their capability to respond to highly variable geomagnetic variations. Since geomagnetic activity was low during 2011 the present trade study has not yielded insight on geomagnetic influence on model performance. Dependence of along-track error on magnetic activity remain to be examined.

The metric and methodology developed here have been adapted in an analysis tool Satellite Orbital Drag Error Estimator (SODEE) to estimate orbit prediction errors. This will help evaluate relative importance between the empirical density model accuracy and other factors like attitude covariance and drag coefficient uncertainty.

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