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Investigation of an MSIS00 Density Modeling Discrepancy

April 20, 2015

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Abstract

During the solar minimum of 2007-2009 an apparent discrepancy between densities predicted by the latest version of the MSIS atmospheric model, MSIS00, and observed data from the on-orbit satellites CHAMP and GRACE was reported by Thayer et al. This mismodeling of the atmospheric density could have a significant impact on satellite lifetimes. Validation of Thayer et al.'s methods and results was performed to verify the existence of an MSIS00 modeling problem. Once Thayer et al.'s findings were verified, a tool package called ADOBE was run on ten spheres at varying altitudes over different solar conditions to discover the extent of the MSIS00 modeling discrepancy. These two efforts showed that MSIS00 was over-predicting the atmospheric density in the thermosphere during deep solar minima and under-predicting the atmospheric density in the lower exosphere during solar maxima, suggesting that MSIS00 needs to be corrected to account for these mismodeling problems. Thayer et al.'s technique to update the MSIS00 density predictions is validated for the deep solar minimum regime.

Contents

1 Introduction

The Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar 2000 (NRLMSISE-00) model, also known as the MSIS00, was introduced in 2002.[2] Produced by the U.S. Naval Research Laboratory, MSIS00 uses data from both ground radar mass spectrometer data and orbital decay to create a comprehensive model for atmospheric drag. Although it has been shown that MSIS00 is more accurate than previous MSIS and Jacchia atmospheric models,[2] the recent solar minimum in 2007-2009, one of the longest and deepest on record,[3] has exposed a potential flaw in MSIS00. Using data from the CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) satellites, Bruinsma and Forbes[4] showed that MSIS00 was over-predicting the density of the atmosphere at CHAMP and GRACE altitudes (350-500 km) for the week of 11-17 December 2008. Thayer et al. showed that the over-predictions of atmospheric density by MSIS00 existed for the entire month of December 2008, as well as February 2007, and were caused by MSIS00 over-predicting the temperature.[1] When the temperature was corrected, it was found that helium needed to be increased to bring the predicted density difference between CHAMP and GRACE satellites into agreement with observations. Chao et al.[5] reported that based on Thayer et al.'s results, satellites at 800 km may be experiencing up to 30% reduced lifetime if these density conditions are maintained throughout a satellite's mission. However, both Thayer et al. and Chao et al. relied on data collected only over two month-long intervals (February 2007 and December 2008) and the extension of these results by Chao et al. to a full solar cycle was a conservative assumption pending further study. In addition, data from only two missions, both operating within a fairly limited altitude range of the atmosphere, were used. Chao et al. also only added additional helium to the atmospheric model and did not look at temperature effects. Before modifications to MSIS00 can be made, it must first be ascertained if this mismodeling occurs 1) just at solar minimum or across the solar cycle, and 2) just at CHAMP and GRACE altitudes, or at higher altitudes as well.

Two different approaches were enlisted to look at these questions. The first looks at CHAMP and GRACE data and determines if MSIS00 is underestimating the density of the atmosphere across an entire solar cycle. Thayer et al.'s results were also replicated to ensure that the procedure used in this study is equivalent to Thayer et al. Then, the technique was used to analyze different time periods. The second approach used an Aerospace-developed software tool called Automated Debris Orbit Ballistic Coefficient Estimator (ADOBE) to analyze a history of two-line element sets (TLEs) for ten orbiting spheres and estimate the area-to-mass ratio for each, based on model values of density. Since the true ratio is known, comparing the estimated area-to-mass ratio with the true ones over the entire solar cycle would verify to what extent MSIS00 may be misrepresenting the density of the atmosphere.

2 Comparison of MSIS00 Density to CHAMP and GRACE Measured Data

2.1 Description of Atmospheric Conditions at CHAMP and GRACE Altitudes

CHAMP and GRACE operate in the region of the atmosphere known as the thermosphere. The thermosphere starts at about 85 km and extends up to about 500 km or more, depending of the level of solar activity. Above the thermosphere is the region known as the exosphere. This region of the atmosphere is where the mean free path of air particles become comparable to the pressure scale height. Where this occurs depends on solar conditions. At lower thermospheric altitudes, the composition of the atmosphere changes from one dominated by N_2 and O_2 to one dominated by monatomic oxygen. At the upper end of the thermosphere, helium becomes a major constituent part. The exact ratios of monatomic oxygen to helium are heavily dependent on season and solar weather.

2.2 MSIS00 Density Modeling Throughout the Solar Cycle

Direct comparison of MSIS00-predicted densities to densities observed by CHAMP and GRACE is the first step in determining whether or not MSIS00 is systematically mismodeling density. Several months of data during CHAMP and GRACE's common operating time frame (2002-2010) were chosen for this analysis: April 2003, April 2005, and April 2008. These months represent solar maximum, solar "average", and solar minimum, respectively. April was chosen because seasonal effects should be minimal. Figures 1-6 show the plotted ratio of observed data to MSIS00-predicted data for both CHAMP and GRACE. A magenta dashed line represents unity. Sutton et al.[6] established that CHAMP and GRACE density data are subject to errors less than 15%. Thus, as long as the data are centered around unity, plus or minus 15% or so, MSIS00 is considered to be in agreement with the observed data. Notice that good agreement is found for April 2003 (Figures 1 and 4) and for CHAMP in April 2005 (Figures 2), but not for the solar minimum month of April 2008 (Figures 3 and 6). For that month, the observed data is close to 40% below what MSIS00 predicted. Figure 5, the GRACE-to-MSIS00 comparison for April 2005, shows that the average of the GRACE-to-MSIS00 ratio is about 20% below unity. This model over-estimation is not well understood at this time but may reflect solar condition outside of the range of conditions that are represented in the MSIS00 data base.

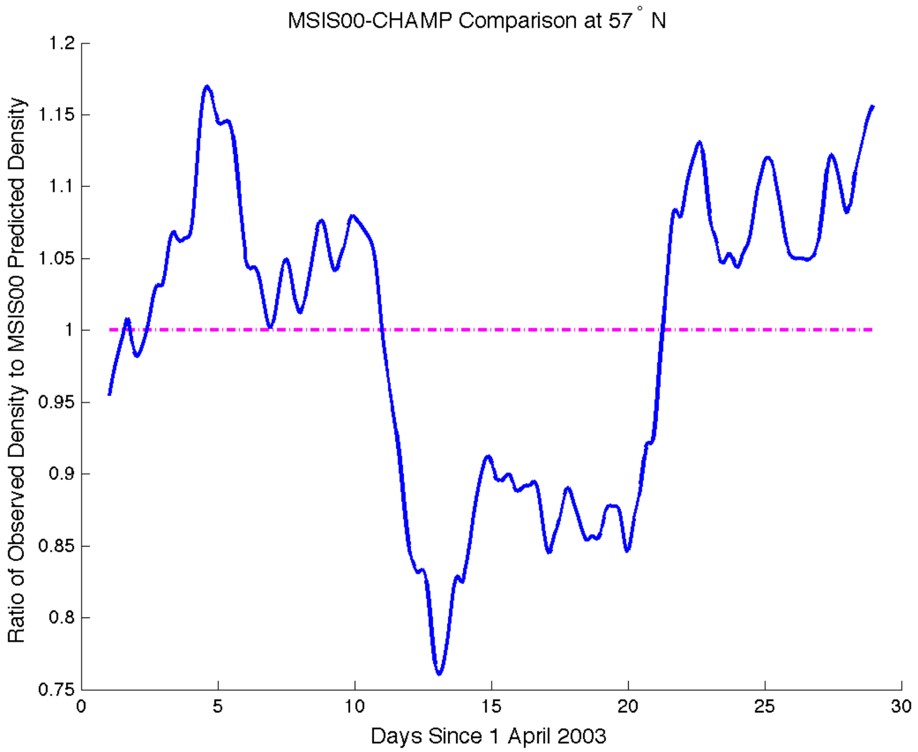

Figure 1: *Ratio of CHAMP-observed density to MSIS00-predicted density for April 2003 at 57° N latitude.*

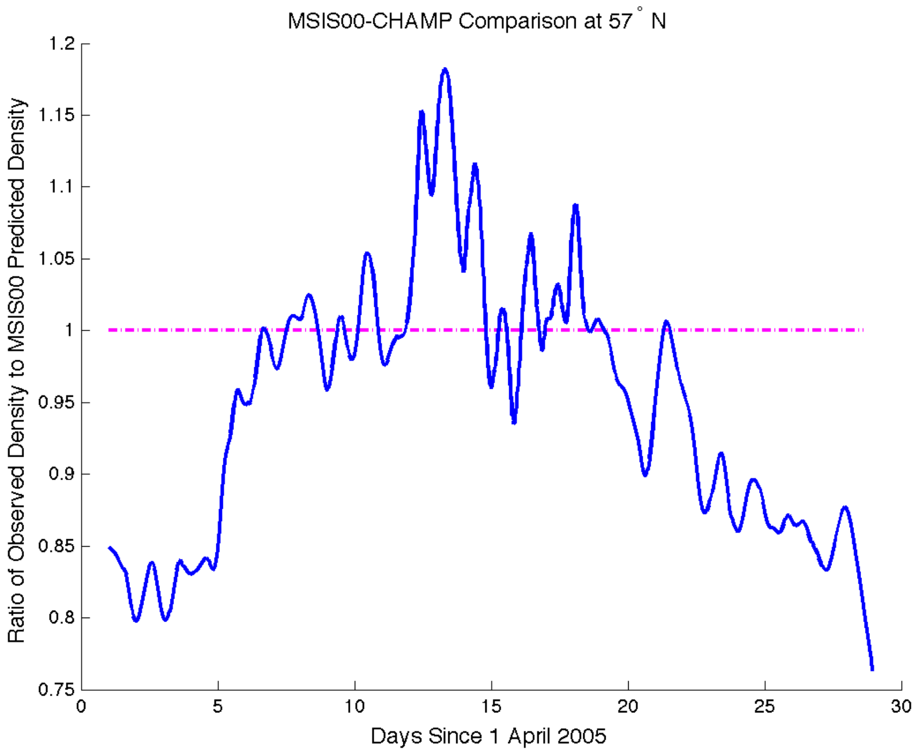

Figure 2: *Ratio of CHAMP-observed density to MSIS00-predicted density for April 2005 at 57° N latitude.*

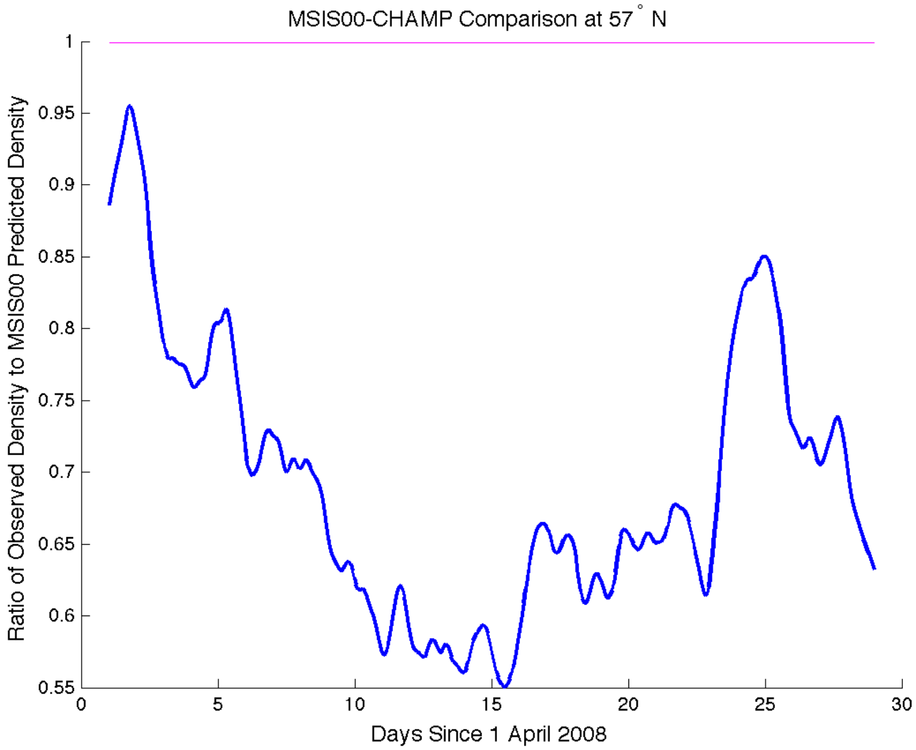

Figure 3: *Ratio of CHAMP-observed density to MSIS00-predicted density for April 2008 at 57° N latitude.*

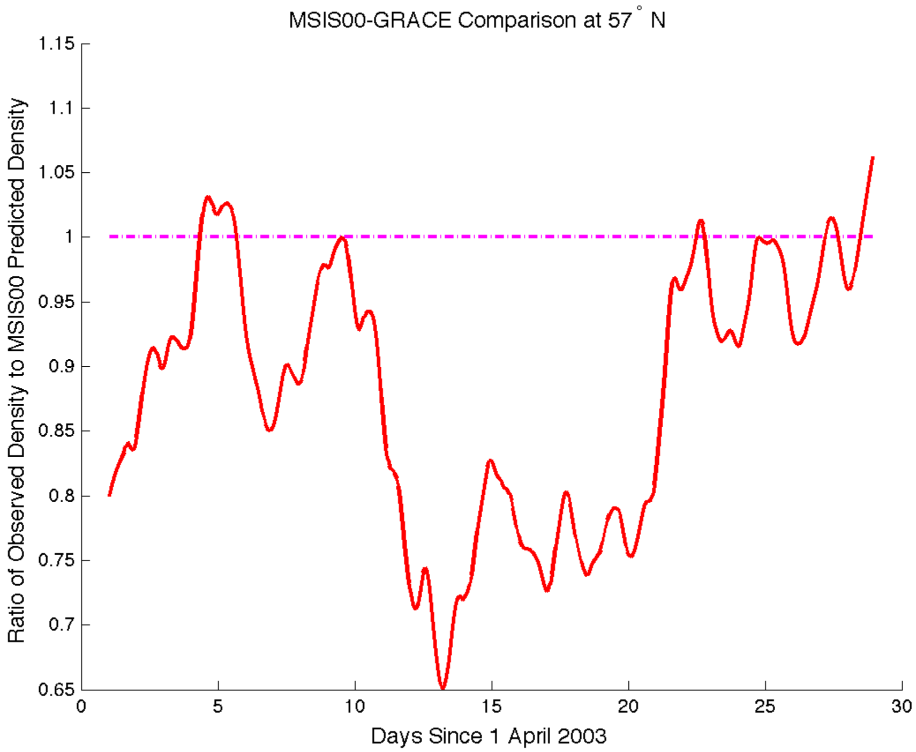

Figure 4: *Ratio of GRACE-observed density to MSIS00-predicted density for April 2003 at 57° N latitude.*

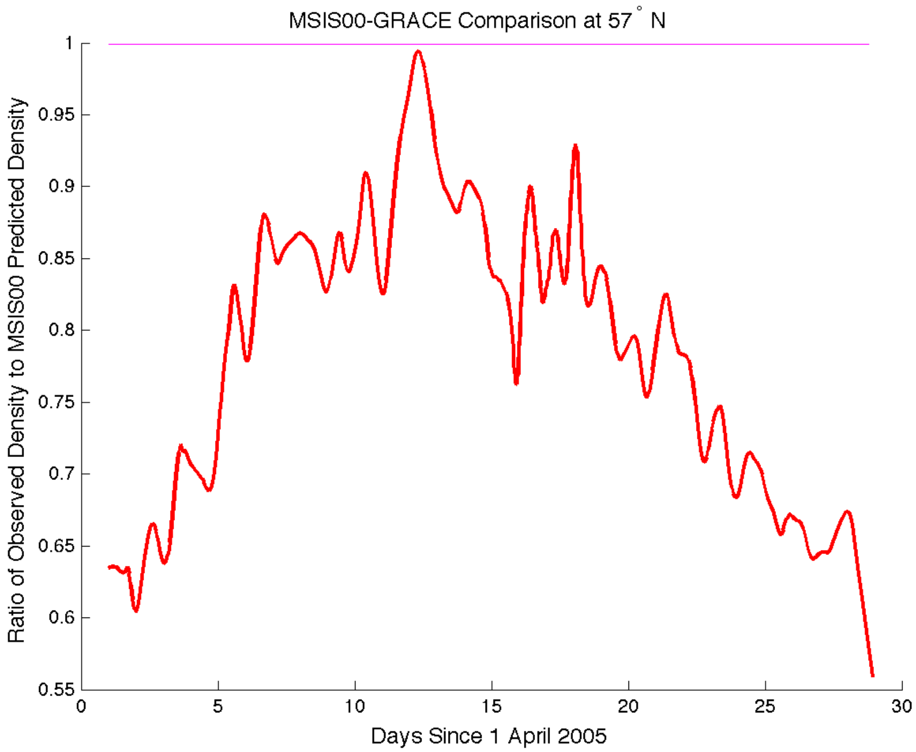

Figure 5: *Ratio of GRACE-observed density to MSIS00-predicted density for April 2005 at 57° N latitude.*

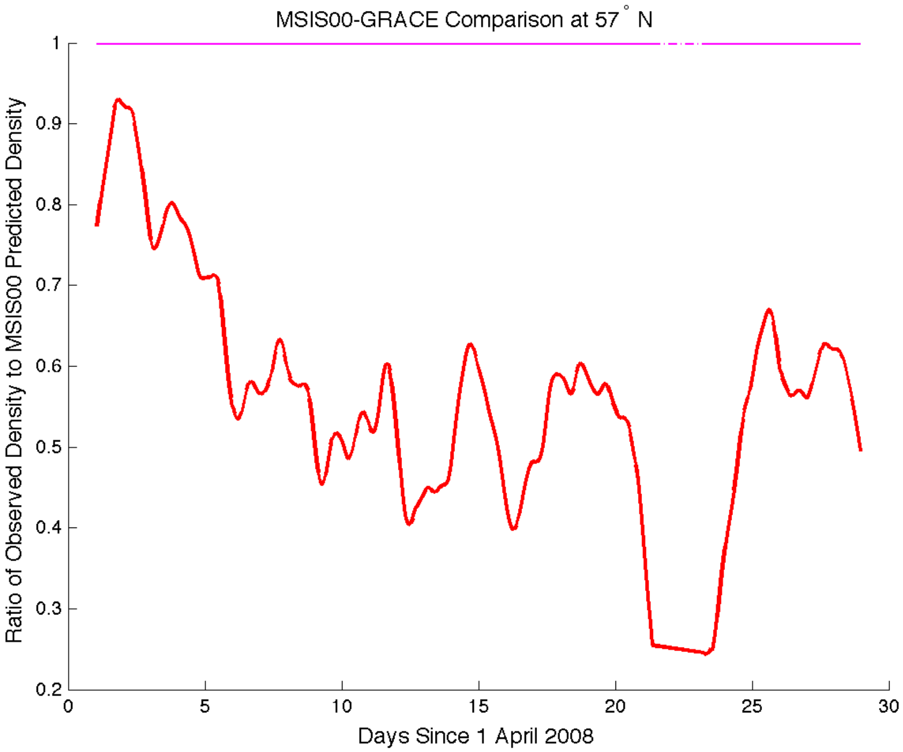

Figure 6: *Ratio of GRACE-observed density to MSIS00-predicted density for April 2008 at 57° N latitude.*

2.3 Replicating and Extending Thayer et al.'s Results

Thayer et al. make use of what they term as the "C/G ratio" to compare the densities of the atmosphere at both CHAMP and GRACE altitudes.[1] The C/G ratio is derived from relating the density scale height H_ρ to the pressure change between two altitudes, as shown in Equation 1:

$$\frac{1}{H_\rho} = -\frac{{}^{d\rho}\!/\!{}_{dz}}{\rho}, \tag{1}$$

where z is the altitude and ρ is the atmospheric density. Re-arranging and integrating both sides then yields

$$-\int_{z_{CHAMP}}^{z_{GRACE}} \frac{dz}{H_\rho} = \int_{\rho_{CHAMP}}^{\rho_{GRACE}} \frac{d\rho}{\rho} = -\ln\left(\frac{\rho_{GRACE}}{\rho_{CHAMP}}\right). \tag{2}$$

Taking the average of the left-hand side of Equation 2 reduces to Equation 4:

$$\left\langle \frac{1}{H_\rho} \right\rangle = -\frac{1}{z_{GRACE} - z_{CHAMP}} \int_{z_{CHAMP}}^{z_{GRACE}} \frac{dz}{H_\rho} \quad = \quad -\frac{\ln\left(\frac{\rho_{GRACE}}{\rho_{CHAMP}}\right)}{z_{GRACE} - z_{CHAMP}}, \tag{3}$$

which implies that

$$\left\langle \frac{1}{H_\rho} \right\rangle = -\frac{\ln \rho_{GRACE} - \ln \rho_{CHAMP}}{z_{GRACE} - z_{CHAMP}}. \tag{4}$$

Equation 4 is the definition of the C/G ratio. Furthermore, the composition and temperature of the atmosphere can be determined through the relationship

$$\frac{\ln \rho_{GRACE} - \ln \rho_{CHAMP}}{z_{GRACE} - z_{CHAMP}} = -\frac{Mg}{R_u T} \tag{5}$$

where M is the average value of the mean molecular weight of the atmosphere between the CHAMP and GRACE satellites, T is the mean temperature, g is gravity, and R_u is the universal gas constant. In other words, by finding the C/G ratio, a determination of the atmospheric conditions present can be deduced. Thayer et al. uses this relation to explore why MSIS00 is mismodeling the atmosphere at CHAMP and GRACE altitudes.

To examine the conclusions drawn by Thayer et al., their results must first be replicated. Density data from both CHAMP and GRACE were obtained from Dr. Eric Sutton of the Air Force Research Laboratory. The C/G ratio was then calculated using Equation 4 for the months of February 2007 and December 2008. These months were chosen by Thayer et al. because CHAMP's and GRACE's orbital planes were approximately the same during those months, allowing for both spacecraft to sample the atmosphere at the same local time during parts of their orbits.[1] This helps to eliminate differences in diurnal effects between the two satellites from the data. Table 1, which shows the orbital elements for CHAMP and GRACE for 16 December 2008, shows this orbital plane alignment. The spacecraft data were filtered to allow only those densities measured at the local time that differed by no more than one hour to be counted in the C/G ratio calculations. Figures 7 and 8 show the reconstructed C/G ratios used in this study. Results are shown for high latitudes, since variations in composition are more easily seen in this region. Lower latitudes experience a wintertime "helium bulge" through transport effects.[7]

Table 1: *Orbital Elements of CHAMP and GRACE on 16 December 2008 at Approximately 21:36:00 UTC.*[5]

	CHAMP (NORAD ID: 26405)	GRACE (NORAD ID: 27391)
Semi-major axis (km)	6697.94	6841.95
Eccentricity	0.0003165	0.001928
Inclination (deg)	87.226	89.012
RAAN (deg)	27.926	27.457
Argument of perigee (deg)	80.613	95.766

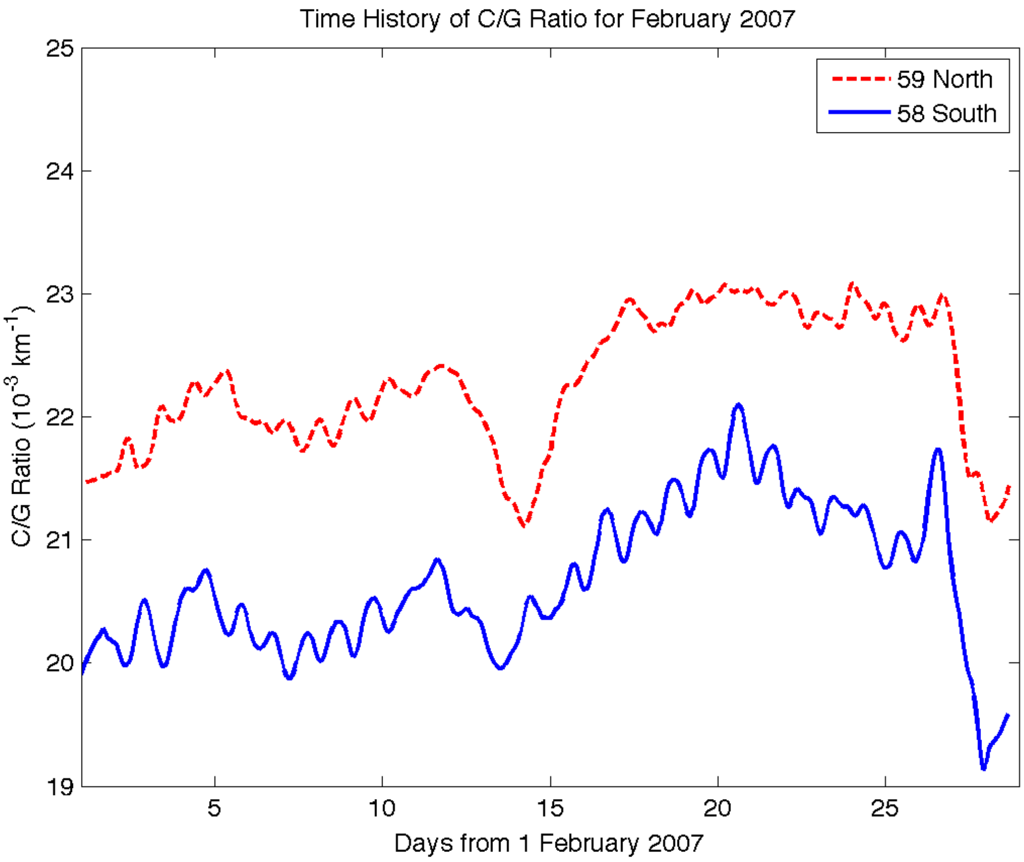

Figure 7: *C/G ratio for the month of February 2007 as calculated for this study.*

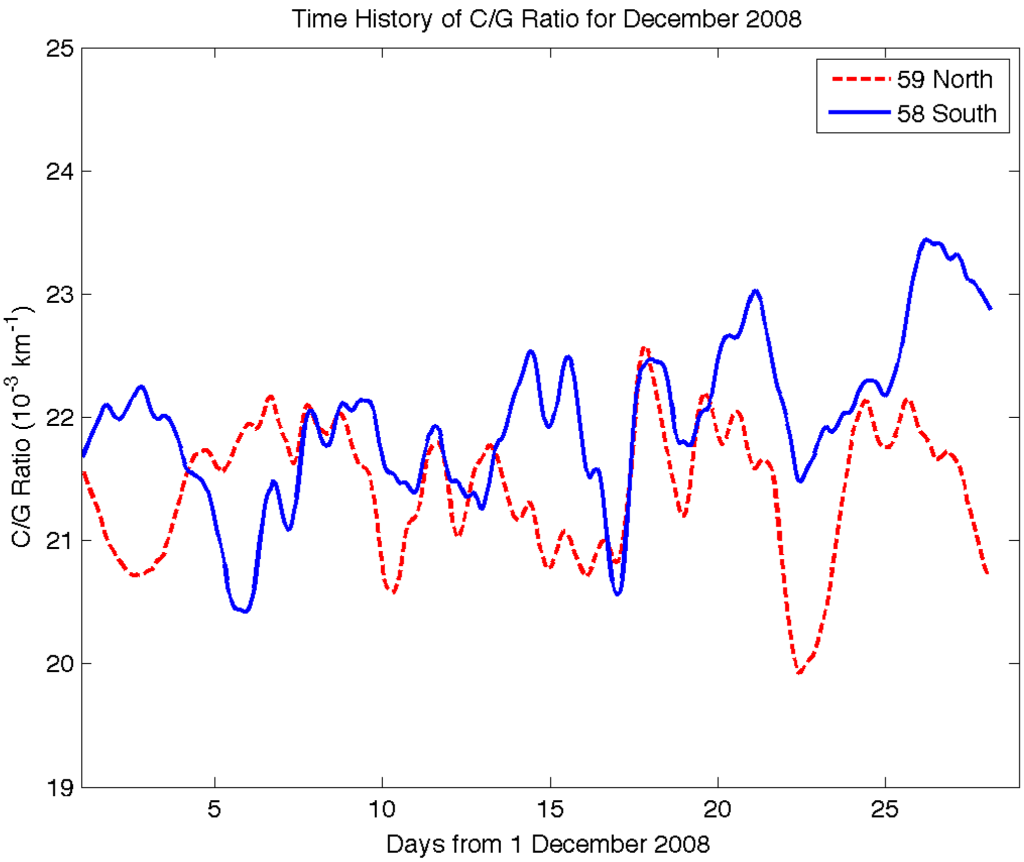

Figure 8: *C/G ratio for the month of December 2008 as calculated for this study.*

Note that higher C/G ratios are observed in the hemisphere that is experiencing winter. Once the C/G ratios calculated for this report were verified to be nearly equal to Thayer et al.'s reported values, C/G ratios for additional months were examined. Two more orbital alignments occurred for CHAMP and GRACE, one in April 2005 and the other in June 2003. The June 2003 alignment takes place near the end of the solar maximum period, which is useful for this study. Figures 9 and 10 show the C/G ratio for these months.

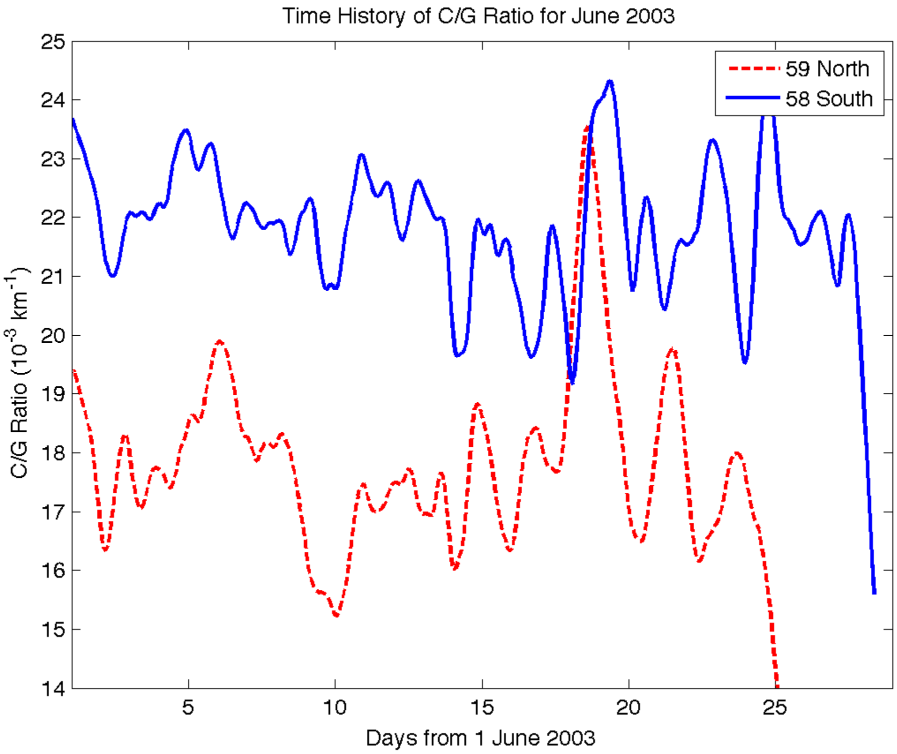

Figure 9: *C/G ratio for the month of June 2003 as calculated for this study.*

Figure 10: *C/G ratio for the month of April 2005 as calculated for this study.*

Since the C/G ratio is dependent on both temperature and atmospheric composition, Thayer et al. varied these parameters to see if they could get MSIS00 predictions to match observed densities and remove biases such as those evident in Figures 3 and 6. To vary temperature to remove the over prediction of density, Thayer et al. reduced the values of $F_{10.7}$ that went into the MSIS00 model. This was able to bring MSIS00 and observed CHAMP and GRACE data into agreement within 5% for most latitudes by reducing $F_{10.7}$ 14 units for December 2008.[1] Similarly, a reduction in $F_{10.7}$ of 10 units was necessary for agreement during February 2007. However, higher latitude densities now were being under-predicted by MSIS00. This required Thayer et al. to increase helium 30% by varying C/G ratios with the revised $F_{10.7}$ (revised temperature) to bring these results into agreement.

To verify that this combination of temperature and compositional effects are the reason for the disparity between MSIS00 and observed data, a second approach is employed using additional observations. For this purpose densities can be inferred using estimations of area-to-mass ratios for satellites with known areas and masses.

3 Estimation of Area-to-Mass Ratio of Known Spheres

3.1 Introduction to FITLEO7 and ADOBE

The ability to estimate satellite area-to-mass (A/m) ratios has been an interest of engineers for many years. Among other things, accurate knowledge of the A/m ratio allows for better drag calculations and thus more precise reentry predictions. In 1991 Chao and Platt developed a differential corrections algorithm to estimate A/m ratios for LEO satellites using TLEs.[8] This technique was later used to evaluate the accuracy of the Jacchia 71 and MSIS90 atmospheric models against NASA's ODERACS orbital decay data.[9] The simplified algorithm was used in an in-house tool called LIFETIME to enhance orbit lifetime and reentry impact predictions. Additional parameters were later added to the algorithm to handle a 15x15 EGM96 gravitational field, third body perturbations, solar radiation pressure, and atmospheric drag. Two independent efforts used this refined technique to estimate perturbations on GEO debris, one using a UD-sequential filter,[10] the other using a least-squares method.[11] Another study used A/m estimation to model the debris caused by a satellite break-up or explosion.[12]

FITLEO7 was written to take position and velocity data calculated from TLEs, run the data through the differential corrections algorithm, and then estimate a final position and velocity. For this study, FITLEO7 was further updated to take into account variations in the drag coefficient at high altitudes, as outlined by Hughes[13] and Moody.[14] ADOBE was developed to take the state estimated from FITLEO7 and calculate A/m. ADOBE marches through FITLEO7 estimates in a series of four loops to generate ballistic coefficient, and thus A/m ratio, estimates for a given spacecraft. The differential corrections process has a fit span of 5 to 20 days, depending on the orbital decay rate. Statistical information is provided for each estimation, including residuals, quality of convergence data, standard deviations, and weighted average ballistic coefficient estimates. This is done by continuously calculating the rate of change in the semi-major axis of the spacecraft, as shown in Equation 6:[15]

$$\frac{da}{dt} = -B\rho n a^2 \left[1 - \left(\frac{\omega_e}{n}\right)\cos i\right]^2, \tag{6}$$

where B is equal to the drag coefficient times the A/m ratio ($C_d \cdot A/m$), ρ is the atmospheric density as calculated by MSIS00, n is the mean motion of the spacecraft, a is the semi-major axis of the spacecraft, ω_e is the angular velocity of the Earth, and i is the inclination of the spacecraft. Equation 6 is only valid for near-circular orbits. Since A/m is constant for an orbiting sphere and the orbital elements of the spheres would be known, deviations of the estimated A/m ratio from truth would be due to errors in how MSIS00 models the atmosphere. Ten spheres were chosen for this study and are listed in Table 2.

Table 2: *List of spheres used to examine MSIS00 predictions at various altitudes.*

Satellite ID	Name	Altitude (km)	Inclination (deg)	True A/m
00011	Vanguard 2	560	33	0.0216
05398	Rigid Sphere 2	775	88	0.0259
02909	Surcal 150B	850	70	0.0815
02826	Surcal 160	850	70	0.0803
00900	Calsphere 1	1025	90	0.1010
07337	Taifun-1/Cosmos 660	405	83	0.0053
08744	Taifun-1/Cosmos 807	405	83	0.0053
12138	Taifun-1/Cosmos 1238	415	83	0.0053
12388	Taifun-1/Cosmos 1263	385	83	0.0053
14483	Taifun-1/Cosmos 1508	390	83	0.0053

3.2 Results of ADOBE Area-to-mass Estimation

ADOBE was run using the spheres listed in Table 2 for two solar maximum years (2001 and 2013) and two solar minimum years (1996 and 2008). The A/m estimates for SURCAL 160 (NORAD ID 02826) and SURCAL 150B (NORAD ID 02909) for 2001 and 2008 are shown in Figures 11-14. A weighted average for the entire year was then calculated for all the spheres. The tabulated A/m estimates for 2001 and 2008 are given in Tables 3 and 4. The noisy A/m estimates in Figures 11 and 13 indicate that MSIS00 is not able to adequately predict the atmospheric density at the altitude of SURCAL 160 and SURCAL 150B (850 km). However, when the noisy estimates are removed, the A/m estimates for 2001 as a whole match the true A/m (green line). For 2008 (Figures 12 and 14), a slight bias in the A/m estimates appears, where ADOBE is estimating A/m ratios too high. Looking at the table data, it appears that A/m estimates are higher than the truth value for the spheres above 775 km and are too low for the spheres below 560 km.

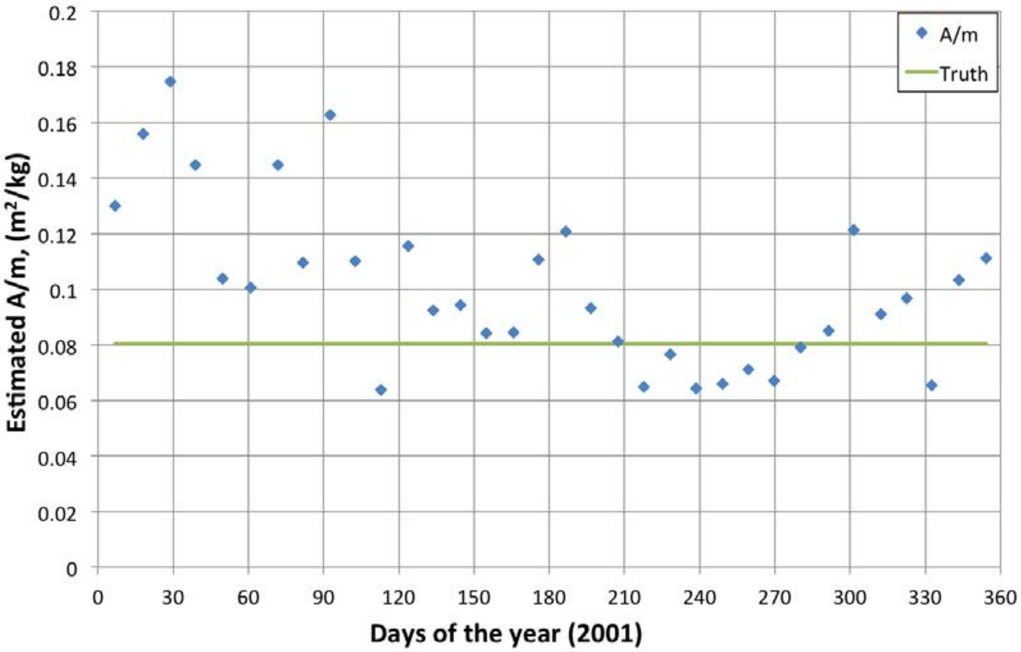

Figure 11: *Estimated A/m ratio for SURCAL 160 in 2001.*

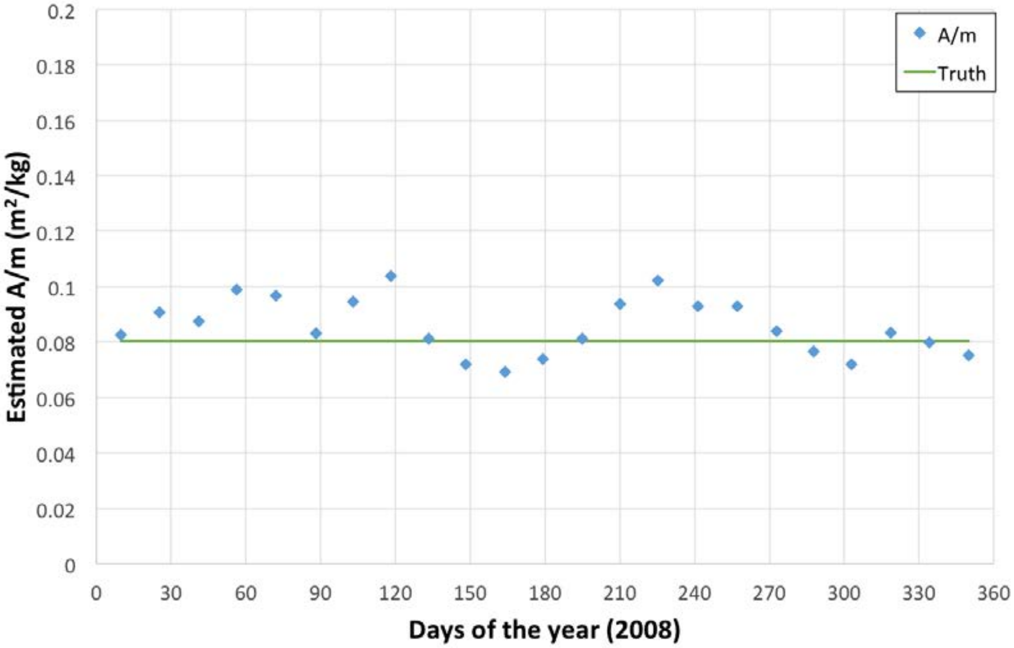

Figure 12: *Estimated A/m ratio for SURCAL 160 in 2008.*

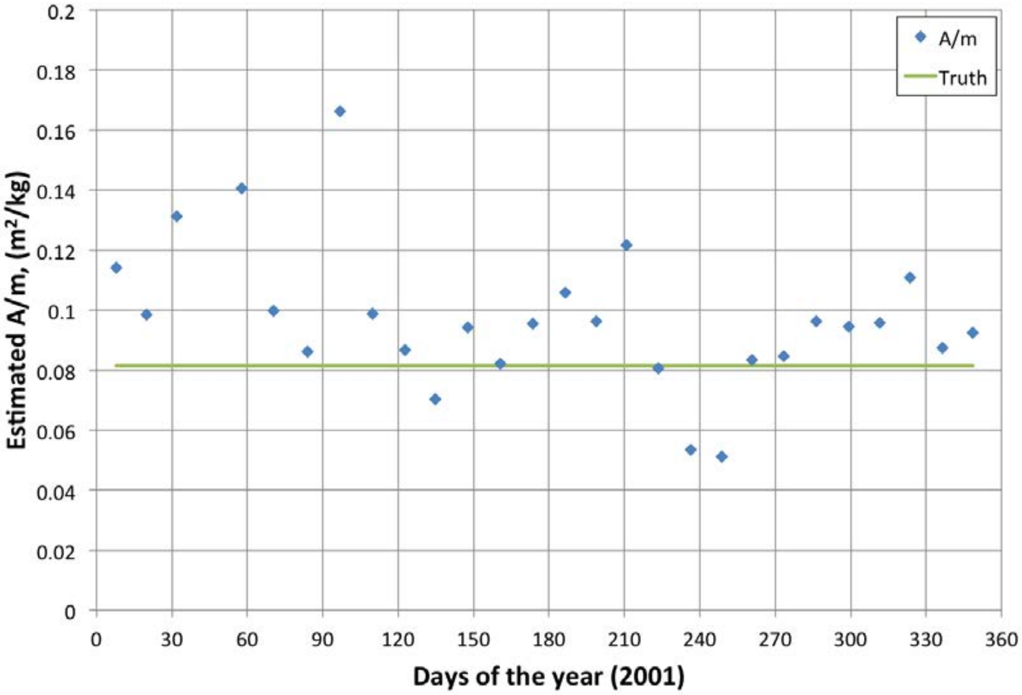

Figure 13: *Estimated A/m ratio for SURCAL 150B in 2001.*

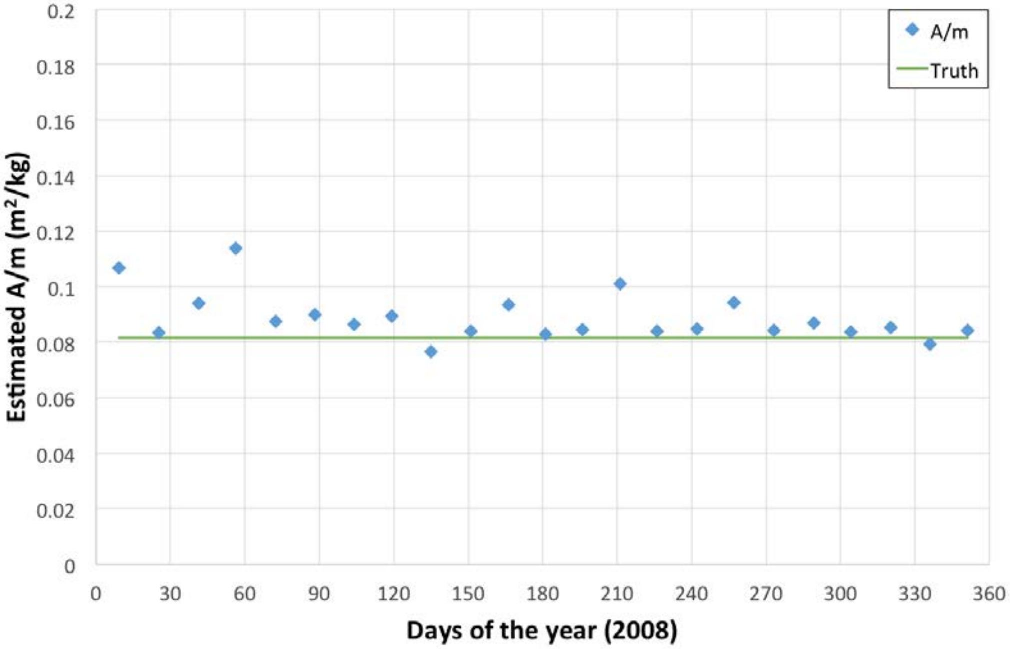

Figure 14: *Estimated A/m ratio for SURCAL 150B in 2008.*

Table 3: *Weighted Averages of Estimated Area-to-Mass Ratio of the Ten Spheres in 2001.*

Satellite ID	Name	Altitude (km)	Estimated A/m	True A/m
00011	Vanguard 2	560	0.0288	0.0216
05398	Rigid Sphere 2	775	0.0355	0.0259
02909	Surcal 150B	850	0.0891	0.0815
02826	Surcal 160	850	0.1267	0.0803
00900	Calsphere 1	1025	0.1426	0.1010
07337	Taifun-1/Cosmos 660	405	0.0051	0.0053
08744	Taifun-1/Cosmos 807	405	0.0055	0.0053
12138	Taifun-1/Cosmos 1238	415	0.0053	0.0053
12388	Taifun-1/Cosmos 1263	385	0.0053	0.0053
14483	Taifun-1/Cosmos 1508	390	0.0054	0.0053

Table 4: *Weighted Averages of Estimated Area-to-Mass Ratio of the Ten Spheres in 2008.*

Satellite ID	Name	Altitude (km)	Estimated A/m	True A/m
00011	Vanguard 2	560	0.0111	0.0216
05398	Rigid Sphere 2	775	0.0329	0.0259
02909	Surcal 150B	850	0.0953	0.0815
02826	Surcal 160	850	0.1883	0.0803
00900	Calsphere 1	1025	0.1966	0.1010
07337	Taifun-1/Cosmos 660	405	0.0045	0.0053
08744	Taifun-1/Cosmos 807	405	0.0039	0.0053
12138	Taifun-1/Cosmos 1238	415	0.0041	0.0053
12388	Taifun-1/Cosmos 1263	385	0.0039	0.0053
14483	Taifun-1/Cosmos 1508	390	0.0043	0.0053

Figures 15 and 16 compare the A/m estimates for all four years. Again, the higher altitude spheres (above 560 km) have A/m estimates significantly higher than their truth values (dark blue bars) for solar maxima conditions, while the lower spheres (385-560 km) have A/m ratio estimates that are too low during the 2008 solar minimum. Estimates of A/m for 1996, a milder solar minimum than the one in 2008, align well with the truth value.

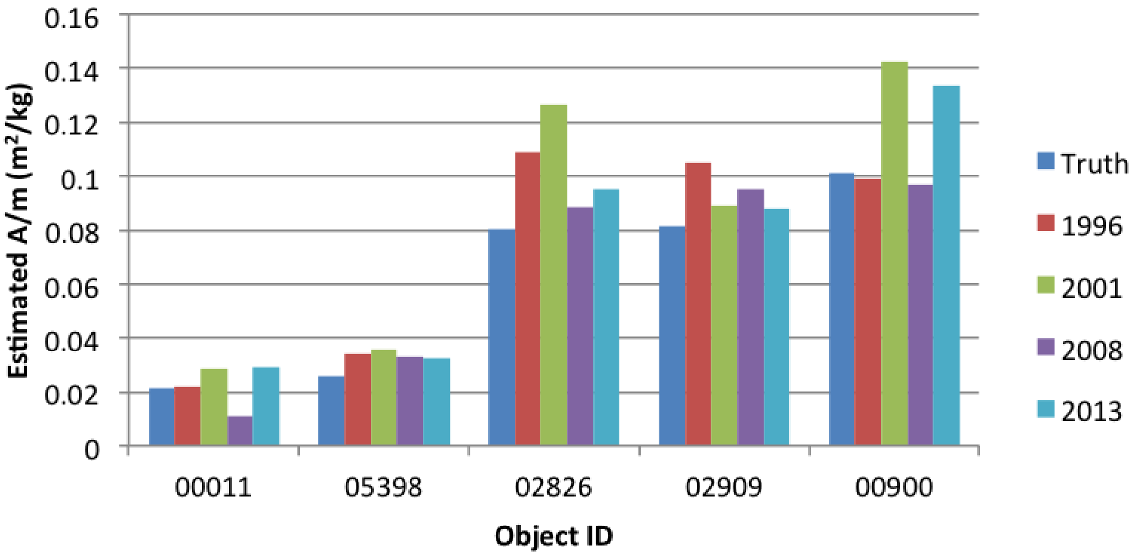

Figure 15: *Estimation of A/m ratio for five spherical satellites during two solar maximum years (2001, 2013) and two solar minimum years (1996, 2008).*

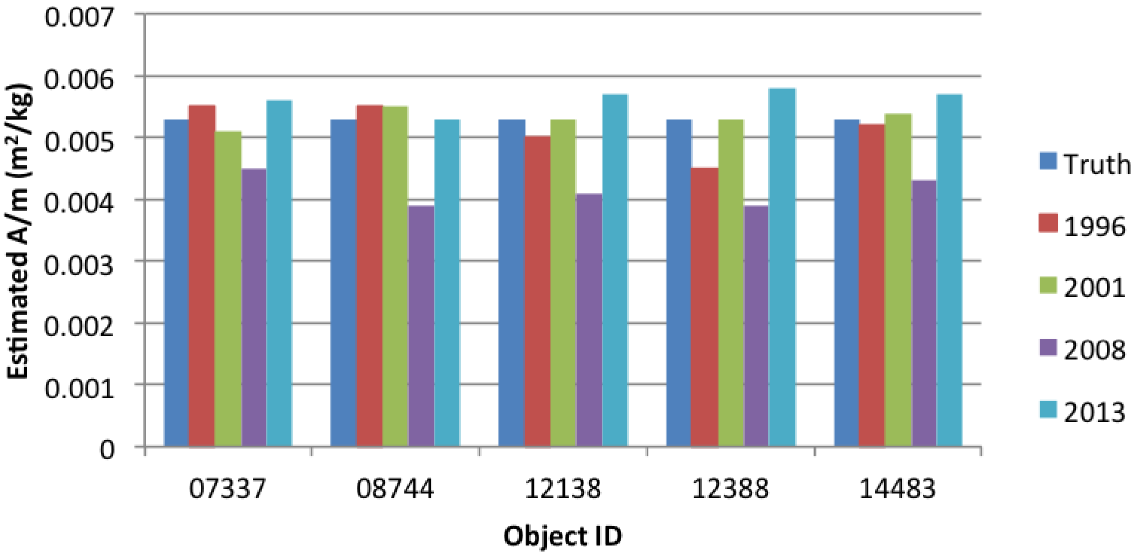

Figure 16: *Estimation of A/m ratio for five Taifun-1 spherical satellites during two solar maximum years (2001, 2013) and two solar minimum years (1996, 2008).*

3.3 Area-to-mass Estimates Using Thayer et al.'s Correction Technique

Thayer et al. use a two-step process to correct the MSIS00 density for the solar minimum of 2007-2008.[1] The first step is to modify the geomagnetic and solar inputs ($\mathrm{A_p}$ and $\mathrm{F_{10.7}}$) to MSIS00 to minimize the bias between the CHAMP and GRACE data and the predicted densities from MSIS00. Thayer et al. found that a reduction of 14 units of $\mathrm{F_{10.7}}$ and an addition of 2 units of $\mathrm{A_p}$ were needed to minimize the differences between the measured CHAMP/GRACE data and the MSIS00-predictions for December 2008.[1] If biases still remain, the second step is to modify the atmospheric composition by adding helium to remove these residual biases. Thayer et al. found that 30% more helium was required to eliminate these remaining differences.[1] The residual biases in our examination of A/m ratios show up as over-predicted values, as seen in Figure 17.

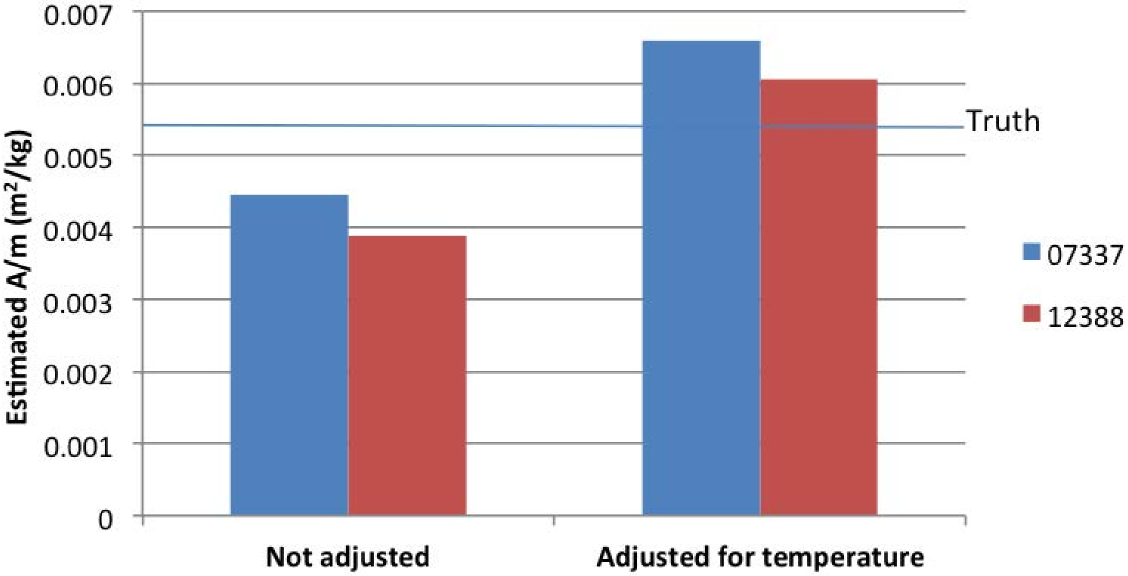

Figure 17: *Estimation of A/m ratio for Taifun-1/Cosmos 660 and Taifun-1/Cosmos 1263 during December 2008 with and without an adjusted $F_{10.7}$ 14 units less than the observed value.*

The reason helium is added to the atmosphere instead of other gaseous species, such as monatomic oxygen, is shown by the hypsometric equation,

$$\rho(z) = \frac{p(z_0)}{R_a(z)\,T(z)} \exp\left(-\int_{z_0}^{z} \frac{dz'}{H(z')}\right). \tag{7}$$

Here ρ is atmospheric density, p is atmospheric pressure, R_a is the specific gas constant at the altitude z, T is temperature, and H is the pressure scale height given by $H = R_u T/Mg$. H is the negative reciprocal of the quantity calculated in Equation 5, except that here T and M are the values of temperature and mean molecular weight at a specific altitude. The controlling factor for the density variation with altitude is the integrated effect of temperature and atmospheric composition in the exponential in Equation 7. Density is greater for temperatures and atmospheric compositions that increase the scale height, or ones that cause the density to decrease more slowly as altitude increases. Given a specific temperature, the scale height is greater when the mean molecular weight M is smaller, such as when there is a greater abundance of helium relative to other gases.

When Thayer et al.'s temperature correction is applied to all ten spheres for 2007 and 2008, ADOBE over-predicts the A/m ratio for most spheres. When helium is added, ADOBE is better able to estimate A/m universally, as seen in Figures 18-21. Thayer et al.'s corrections for December 2008 were applied for all objects over 2008 (Figures 20 and 21) and were used as the basis for the 2007 corrections (Figures 18 and 19). The 2007 corrections were a reduction of 10 units of $\mathrm{F}_{10.7}$, an addition of 2 units of A_p, and the addition of 20% more helium. During non-minimum years, atmospheric corrections are not needed. Figure 22 shows the estimated A/m ratios for the Taifun-1 spheres during 2005. Whereas these spheres' A/m estimates were significantly off during the solar minimum years (see Figures 18 and 20), the A/m estimates for 2005 were fairly close to the truth.

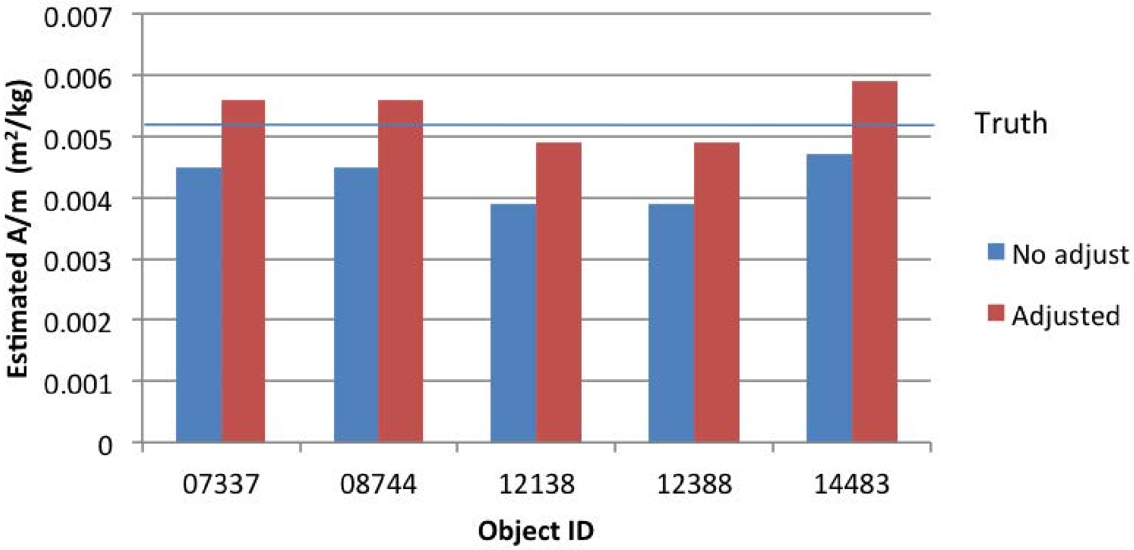

Figure 18: *A/m ratio estimation for Taifun-1 spheres during 2007 with and without the adjustments of 10 units less $F_{10.7}$, 2 units more A_p, and 20% more helium.*

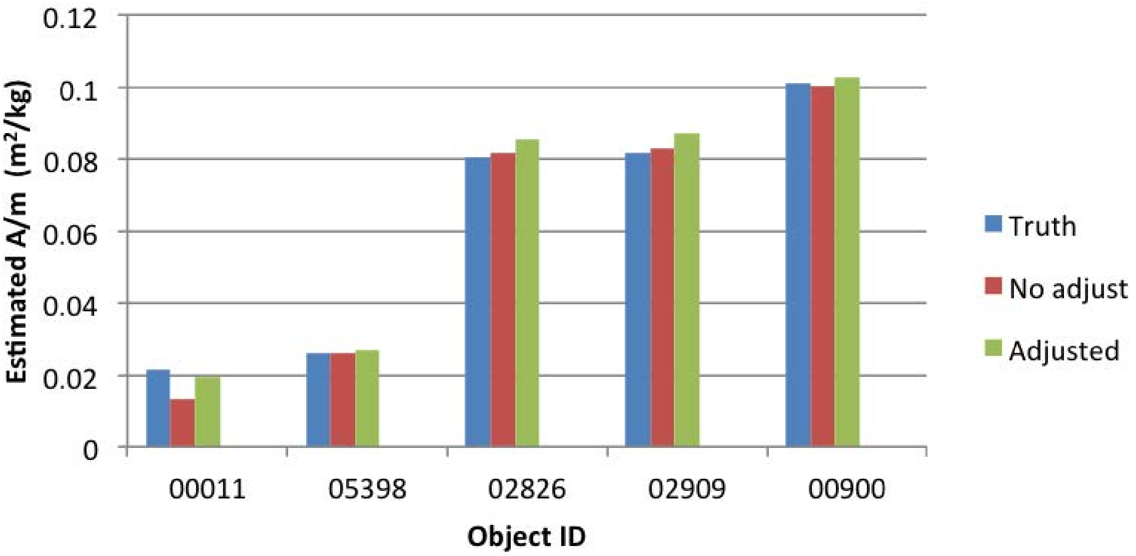

Figure 19: *A/m ratio estimation for spheres at altitudes 560 km to 1025 km during 2007 with and without the adjustments of 10 units less* $F_{10.7}$*, 2 units more* A_p*, and 20% more helium.*

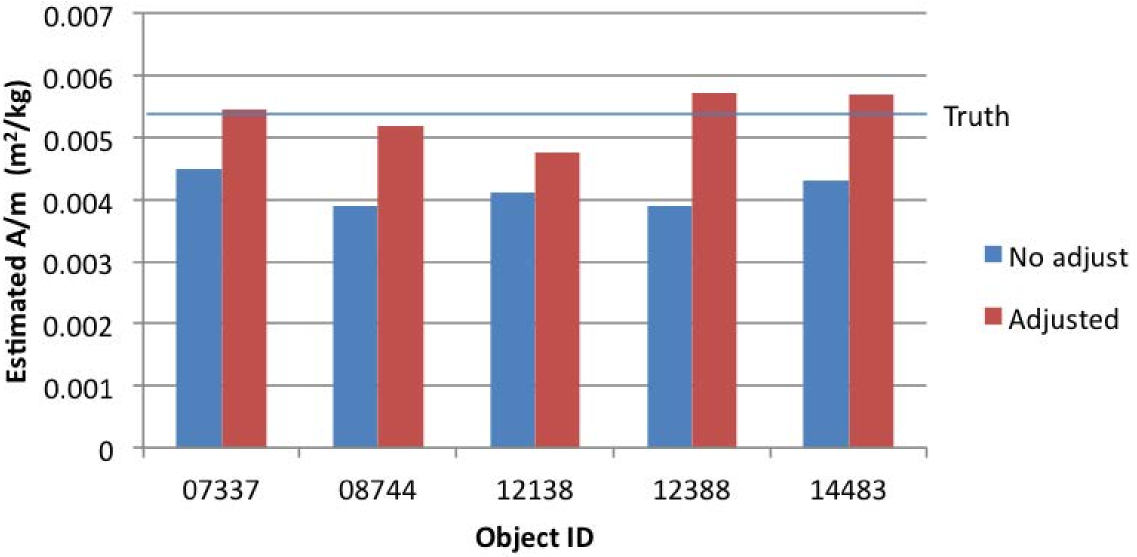

Figure 20: *Estimation of A/m ratio for Taifun-1 spheres during 2008 with and without the adjustments of 14 units less* $F_{10.7}$*, 2 units more* A_p*, and 30% more helium.*

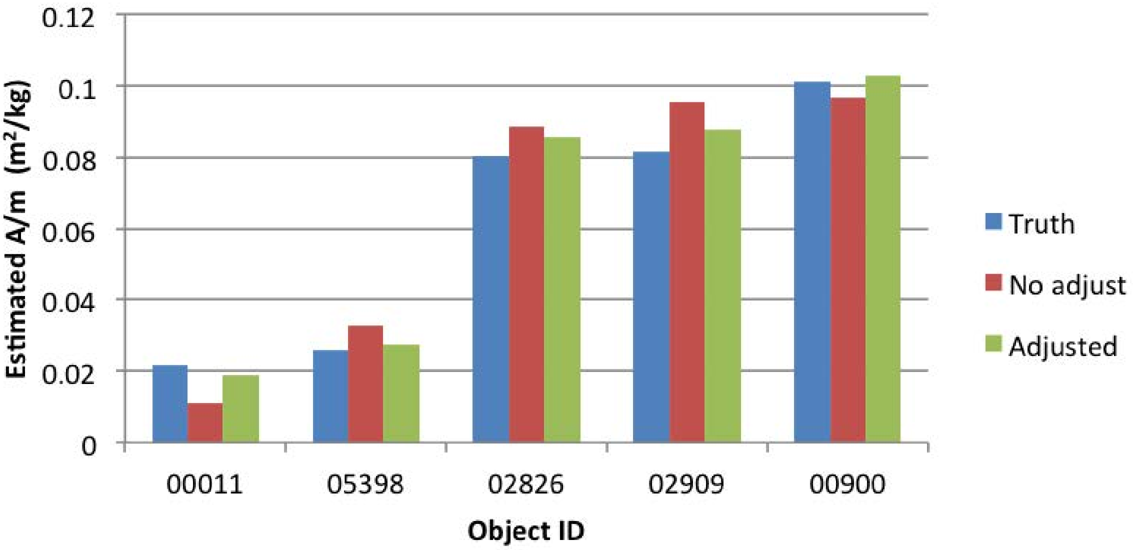

Figure 21: *Estimation of A/m ratio for spheres at altitudes 560 km to 1025 km during 2008 with and without the adjustments of 14 units less* $F_{10.7}$*, 2 units more* A_p*, and 30% more helium.*

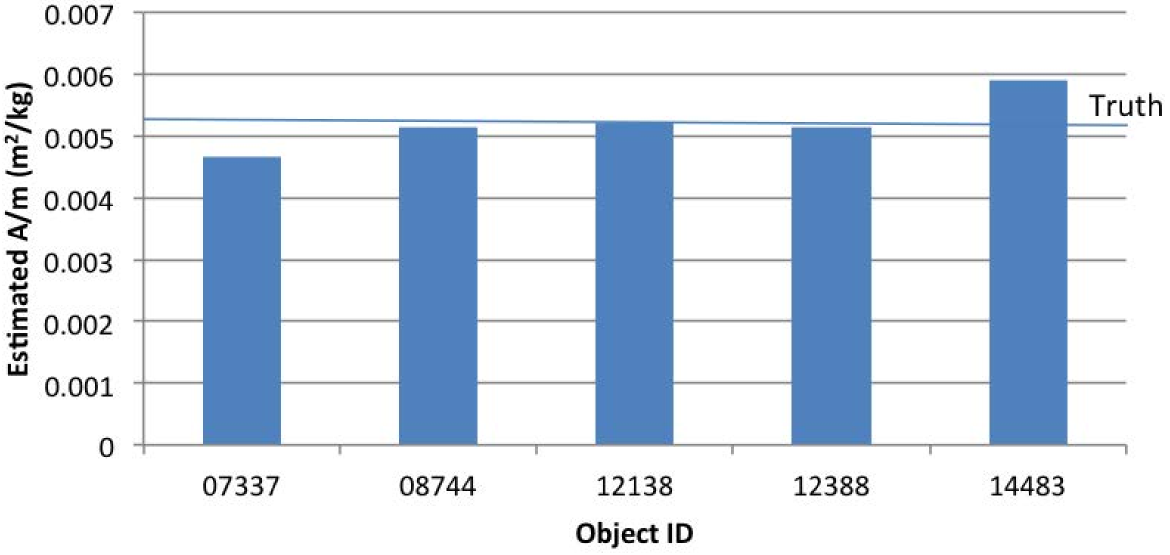

Figure 22: *Estimation of A/m ratio for spheres at altitudes 385 km to 415 km during 2008 without any adjustments.*

These findings provide an independent verification of Thayer et al.'s findings and corrective techniques. A greater abundance of helium relative to atomic oxygen (smaller M) at lower altitudes can increase density at higher altitudes, even where helium is dominant. This is because density is an integrated effect of M and T (see Equation 7). Vanguard 2 (NORAD ID 00011), operating at 560 km altitude, saw a large increase in its estimate of A/m ratio when helium was added and an $\mathrm{F_{10.7}}$ and $\mathrm{A_p}$ adjustment were made (Figures 19 and 21).

A lower crossover between atomic oxygen and helium dominance would have significant effects on the lifetimes of satellites operating in the 350 km-550 km region. At higher altitudes, satellite lifetimes may also be impacted, as mentioned by Chao et al.[5] Figures 19 and 21 indicate that the mismodeling of the atmosphere above 560 km (above Vanguard 2), while noticeable, is not as large as it is below 560 km. Refinements to the MSIS00 model based on adjustments for solar and geomagnetic drivers and helium abundance will lead to a more accurate understanding of the effects of MSIS00's mismodeling on satellite lifetime predictions.

3.4 Estimated Orbit Lifetime Changes Due to Helium Discrepancy in MSIS00

The results of this investigation based on both CHAMP/GRACE data and decaying spheres provide a good understanding that MSIS00 models the temperature too high and density too high during solar minimum of 2008. This modeling error can be successfully corrected by the proposed method of lowering the temperature and adjusting helium density. It thus becomes clear that the simplified assumption of adjusting the helium content alone for the whole solar cycle in the earlier simulation analysis[5] is incorrect.

Based on the findings of this study, orbit lifetime changes at various orbit altitudes with different ballistic coefficients were computed with LIFETIME using MSIS00 density model. A modified version of LIFETIME was created to correct the helium discrepancy with the methodology described in this report. The estimated differences of orbit lifetime of various cases were computed by repeating the same orbit conditions with the above two versions of LIFETIME. The largest adjustments are assumed near October 2008 with a reduction in $\mathrm{F_{10.7}}$of 14 units, an increase in $\mathrm{A_p}$ of 2 units, and an increase in helium density of 30%. The adjustments decrease gradually following an empirical function of square root of sine, which becomes zero at 3 years on both sides of the solar minimum.

The estimated lifetimes and percentage increases due to helium modeling error in MSIS00 are shown in Table 5. The large increases in orbit lifetime are found at altitudes between 300 and 400 km, being 12.5 to 40.8 %. The center of the lifetime duration of each of these cases is near the extreme solar minimum of October 2008. When the center of the lifetime duration is moving away from the solar minimum, the increases in lifetime gradually diminish at these altitudes as shown by Table 6. The above simulation analysis clearly reveals that significant lifetime increases up to 40.8% caused by helium modeling error in MSIS00 occur near solar minimum for orbits at altitudes between 300 km and 400 km. The changes become insignificant at altitudes higher than 500 km or the duration of the orbit lifetime is away from the solar minimum.

Table 5: *Orbit lifetime changes with $F_{10.7}$, A_p and helium density adjustments.*

Altitude, km	Cd · A/m	MSIS00-predicted lifetime, days	Lifetime with adjustments, days	% change
300	0.005	260.7	330.3	26.9
300	0.01	142.3	170.9	20.1
300	0.03	49.5	62.3	25.9
300	0.05	28.6	36.4	27.3
400	0.005	2360.3	2655.5	12.5
400	0.01	1402.7	1590.6	13.4
400	0.03	557.0	762.6	36.9
400	0.05	353.4	497.5	40.8
500	0.03	2706.1	2871.8	6.1
500	0.05	2062.1	2206.7	7.0
500	0.07	1612.2	1755.1	8.9
600	0.03	4638.9	4801.9	3.5
600	0.05	4134.9	4280.7	3.5
600	0.10	8266.4	8430.1	2.0
700	0.20	4723.8	4861.4	2.9
800	0.30	7689.2	7971.0	3.7
800	0.50	3787.2	3981.7	5.1

Table 6: *Orbit lifetime changes with $F_{10.7}$, A_p and helium density adjustments at different epochs.*

Altitude, km	Cd · A/m	Epoch	MSIS00-predicted lifetime, days	Lifetime with adjustments, days	% change
300	0.005	12/19/2009	251.1	290.0	15.5
300	0.01	10/1/2010	178.1	194.3	9.1
300	0.03	12/1/2011	129.0	129.0	0.0
400	0.005	6/1/2007	567.6	743.0	38.0
400	0.01	1/1/2009	547.5	677.5	23.7
400	0.03	12/1/2009	432.6	496.5	14.8
400	0.05	1/1/2011	266.2	282.7	6.2
400	0.03	1/1/2012	180.4	180.4	0.0

4 Conclusion

An investigation of a helium discrepancy in the NRLMSISE-00 density model (MSIS00) during periods of deep solar minimum, typified by the conditions present in 2007-2009, was performed with two parallel analyses: one analysis with data from the CHAMP and GRACE spacecraft, and the other analysis with estimated area-to-mass (A/m) ratios of ten decaying spheres with known diameter and mass. Results show that MSIS00 temperature predictions are too high, which leads to density estimates that are about 35% too high for the solar minimum of 2008.

During this solar minimum year, the estimated A/m ratio values in the altitude range of 385 km to 415 km are consistently lower by 15 to 26%, which clearly supports the early finding by Thayer et al.[1] The helium modeling error of MSIS00 becomes less significant at altitudes above 560 km and does not exist outside the extreme solar minimum. Satellites may experience lifetime increases of up to 41% in lower altitude orbits, but at higher altitudes the lifetime increases are less than about 5%.

A methodology proposed in this analysis based on solar flux (and therefore temperature) and helium density adjustments has successfully corrected the discrepancy predicted by MSIS00 during the extreme solar minimum of 2007-2008. This procedure can be performed without modifying the code of the MSIS00 model. The significant deviations in the A/m ratios from the truth at higher altitudes, especially during the first three months of the solar maximum year of 2001, suggest that the MSIS00 density model requires updates or enhancements at higher altitudes above 800 km in addition to the helium modeling error.

References

[1] Thayer, J. P., Liu, X., Lei, J., Pilinksi, M., and Burns, A. G., "The Impact of Helium on the Thermosphere Mass Density Response to Geomagnetic Activity During the Recent Solar Minimum," *Journal of Geophysical Research*, Vol. 117, No. A7, July 2012.

[2] Picone, J. M., Hedin, A. E., Drob, D. P., and Aikin, A. C., "NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues," *Journal of Geophysical Research*, Vol. 107, No. A12, December 2002.

[3] Hady, A. A., "Deep Solar Minimum and Global Climate Changes," *Journal of Advanced Research*, Vol. 4, 2013, pp. 209–214.

[4] Bruinsma, S. L. and Forbes, J. M., "Anomalous Behavior of the Thermosphere During Solar Minimum Observed by CHAMP and GRACE," *Journal of Geophysical Research*, Vol. 115, No. A11, November 2010.

[5] Chao, C. C., Walterscheid, R. L., and Yoo, B. B., "Impact of Helium Modeling Error in MSIS2000 Density Model," Tech. rep., TOR-2014-01109.

[6] Sutton, E. K., Nerem, R. S., and Forbes, J. M., "Density and Winds in the Thermosphere Deduced from Accelerometer Data," *Journal of Spacecraft and Rockets*, Vol. 44, No. 6, November-December 2007, pp. 1210–1219.

[7] Straus, J. M., Creekmore, S. P., and Ching, B. K., "A Dynamical Model of Upper-Atmospheric Helium," *Journal of Geophysical Research*, Vol. 82, No. 16, June 1977, pp. 2132–2138.

[8] Chao, C. C. and Platt, M. H., "An Accurate and Efficient Tool for Orbit Lifetime Predictions," *Proceedings of the AAS/AIAA Spaceflight Mechanics Meeting*, 11-13 February 1991.

[9] Chao, C. C., Gunning, G. R., Moe, K., Chastain, S. H., and Settecerri, T. J., "An Evaluation of Jacchia 71 and MSIS90 Atmosphere Models with NASA ODERACS Decay Data," *Journal of Astronautical Sciences*, Vol. 45, No. 2, April-June 1997, pp. 131–141.

[10] Chao, C. C. and Campbell, W. S., "Estimating Solar Radiation Pressure for GEO Debris," *Proceedings of the Fifth European Conference on Space Debris*, 30 March-3 April 2009.

[11] Khutorovsky, Z. N., Boikov, V. F., and Testov, A. V., "Monitoring of GEO Satellites," *Proceedings of the Third European Conference on Space Debris*, 19-21 March 2001.

[12] McVey, J. P. and Chao, C. C., "Automated Ballistic Coefficient Estimation Technique to Analyze the Debris from the Cosmos-2251 and Iridium-33 Collision," *AAS/AIAA Astrodynamics Specialist Conference*, 31 July-4 August 2011.

[13] Hughes, P. C., *Spacecraft Attitude Dynamics*, chap. 8, John Wiley and Sons, 1986.

[14] Moody, D. M., "Estimating Drag Coefficient in Free-molecular Flow," Tech. Rep. ATM 2012(8402-84)-2, The Aerospace Corporation, 2012.

[15] Chao, C. C., *Applied Orbit Perturbation and Maintenance*, The Aerospace Press, 2005.

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