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HIGH ACCURACY SATELLITE DRAG MODEL (HASDM) REVIEW

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The dominant error source in force models used to predict low altitude satellite trajectories is atmospheric drag. At satellite altitudes atmospheric density models do not adequately account for dynamic changes in neutral density, leading to significant errors 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 200km to 800km. 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 then use to first differentially correct all the drag influenced orbits (over 6000) in the NORAD catalog, and then predict all satellite trajectories out three days. A six-month demonstration period was conducted in 2001, where the concept was validated using data from ~120 satellites. The resulting improvements in epoch accuracy, ballistic coefficient consistency, and predicted satellite positions led to a full drag catalog 60-day test in 2002. The excellent results from the full drag catalog test are leading to the operational implementation of the HASDM program during the summer of 2004.

INTRODUCTION

The High Accuracy Satellite Drag Model was initially developed as an 18-month test effort that was completed in August 2002. Its goal was to improve Air Force Space Command's ability to meet high accuracy space surveillance requirements for satellite trajectory prediction. For low-perigee satellites (< 600 km altitude), these requirements are not consistently met, largely because current atmospheric density models have errors ranging from 8% (200 km) to 24% (800 km).[6,7]

The HASDM model processes drag information from the trajectories of 75 to 80 inactive payloads and debris (*calibration satellites*) to solve for a dynamically changing global

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correction to the thermospheric and exospheric neutral density. This correction covers the altitude range of ~200 to 900 km. Satellite tracking observations (azimuth, elevation, range, and range rate) from the Space Surveillance Network (SSN) are processed directly to derive the neutral atmospheric density. Thermospheric density correction parameters are computed along with the trajectory states of the calibration satellites in a single estimation process, known as the Dynamic Calibration Atmosphere (DCA).

This project also included the development of a prediction model that maps the time series of solar and geomagnetic indices to the density correction parameters estimated by DCA. It also extrapolates information from the time series of the density correction coefficients using discrete Fourier and wavelet techniques. DCA's dynamic thermospheric density correction, together with the 3-day density parameter prediction, significantly improves satellite trajectory estimation and prediction.

BACKGROUND

The US Air Force first explored the concept of estimating thermospheric density from satellite trajectories in 1995 at Air Force Space Command and Air Force Research Laboratory. This led to development of the earlier drag model, the Modified Atmospheric Density Model (MADM) [8], completed in March 2000.

In MADM, the main parameter used to determine the density was the estimated ballistic coefficient. In the orbit determination process, this is a solve-for parameter, just like the elements of the satellite's state vector. The ballistic coefficient is a function of the ratio of satellite area to mass, which is a measure of how much the object is affected by atmospheric drag. The larger the ballistic coefficient, the greater affect the atmosphere has on the object [5]. The true ballistic coefficient B_{true} and the true atmospheric density ρ_{true} , together with the speed V of the satellite, determine the drag acceleration a_D through the following expression:

$$a_D = \frac{1}{2} B_{\text{true}} \rho_{\text{true}} V^2 \qquad (1)$$

The true density ρ_{true} is generally not known, so a model density ρ_{model} is used instead. The estimated ballistic coefficient, B_{model}, varies depending on the error in the modeled density ρ_{model}. If the model density is low when compared to the real density, then the estimated ballistic coefficient B_{model} is larger than its true value. Conversely, when the model atmospheric density is too high, B_{model} is smaller than its true value. Therefore, information about the bias in the atmospheric model is contained within the values for B_{model}.

DYNAMIC CALIBRATION ATMOSPHERE

MADM employed a separate orbit determination process and a separate density estimation process. In HASDM's Dynamic Calibration Atmosphere (DCA), these two processes are combined into a single estimation process. This is a weighted least squares differential correction across all calibration satellites that simultaneously solve for global density corrections and a state vector for each calibration satellite. DCA uses Space Surveillance Network (SSN) observations directly in the solution. As in MADM, DCA uses the Jacchia 1970 thermosphere as its base model [4]. While MADM corrected only two global temperature parameters of the base model, DCA estimates 13 global density correction parameters. This global correction not only reduces the errors in the state error covariance for low-perigee satellites, but also makes these errors more realistic. DCA was developed by Omitron, Inc. in Colorado Springs, Colorado, and uses the HASDM thermospheric density model, a modified Jacchia 1970 model developed by Air Force Space Command/XPY[9].

An important feature of DCA is its segmented solution approach. Although the state vector of each calibration satellite is estimated for a 1.5-day fit span interval, the density correction parameters are estimated on 3-hour sub-intervals within the fit span. This approach is used to extract the time resolution needed to accurately determine the dynamically changing thermospheric density.[2] This is especially important during geomagnetic storms, when the Joule heating and particle precipitation of the auroral ovals drive rapidly changing density features. However, to obtain this 3-hour resolution requires that the density parameters be constrained within the parameter solution. The constraints can be minimized though because of the large number (~75 to 80) of calibration satellites used in the fits, and because of the heavy space surveillance sensor tasking which provided observations on almost every pass over almost every SSN sensor.

For non-calibration satellites the model also employs a Segmented Solution for Ballistic coefficient (SSB). This is a technique whereby an overall ballistic coefficient (B_{model}) is estimated over the fit span and additional B_{model} corrections are allowed to vary throughout the fit span. Fit spans of several days are divided into ½ to 3-hour segments for which a separate ballistic coefficient correction is estimated for each segment. The SSB technique is applied after the DCA density corrections are applied for each individual non-calibration satellite, thus further improving the accuracy of the state vector estimate for the satellite trajectory. This technique is only applied if there is sufficient tracking data to provide the observability needed for the segmented B_{model} correction estimates.

TEMPERATURE AND DENSITY PROFILES

For the initial HASDM test period, 75 calibration satellites were used simultaneously to solve for a global density correction field. This field corrects two local parameters in the vertical temperature profile leading to a unique density profile, a low-altitude parameter and a high-altitude parameter. DCA estimates a new set of 13 parameters every 3 hours. The low-altitude parameter is the so-called "inflection point temperature" T_x at 125 km altitude. The high-altitude parameter is the exospheric temperature T_∞, the asymptotic temperature the profile approaches with increasing altitude in the exosphere (>600 km altitude). The local temperature profile $T(z)$ as a function of altitude z is uniquely determined by the local values for T_x and T_∞. The local temperature profile leads to the local density profile through interpolation of density tables, which were produced by integrating the hydrostatic equation (from 90 km to 105 km altitude) and the diffusion equation (above 105 km)[3]. The local values for T_x and T_∞ are both corrected indirectly through a *global* parameter known as the "nighttime minimum exospheric temperature" T_c. This is the principal parameter used in the standard Jacchia 1970 model to describe the state of the entire thermosphere in response to solar extreme ultraviolet heating [4]. The global density field is specified through two sets of spherical harmonic coefficients, one set for T_x and the other for T_c. It was discovered that the lower altitude (<300 km) density variations were mainly captured from the correction of the T_x set of coefficients, and the higher altitude (>300 km) variations were mainly captured with the T_c coefficient set. Because long life satellite orbits available for calibration purposes are relatively scarce at low altitudes (<300 km) only 10 satellites were found to be useful in the low altitude regime. Therefore, only 4 coefficients of the T_x set were found to have enough observability to be useful. For higher altitudes many more calibration satellites were available, which led to using a 2x2 (degree x order) spherical harmonic field (9 coefficients) as the optimum for the T_c set of coefficients. Thus, these 13 coefficients were adopted as the optimum coefficient set to use for the selected calibration satellites. It was also discovered that the coefficients needed to be constrained in the solution to obtain accurate density corrections every 3 hours. This is due to drag observability problems resulting from satellite orbital periods all greater than 1.5 hours, and no Southern Hemisphere sensor coverage. It was determined that good solution observability could be obtained if a half-life of 3 hours was used to constrain the 0th degree terms of both T_x and T_c, while a half-life of 18 hours was required to constrain the rest of the higher degree and order coefficients.

DENSITY PREDICTION TECHNIQUE

The density correction coefficients from DCA are predicted out 3 days into the future using a prediction filter that relates these coefficients to the time series for the solar/geomagnetic heating indices, $F_{10.7}$ and a_p, as well as an extrapolation of the past time series of the coefficients themselves. All 13 DCA coefficients are expressed as a separate function of the time series of their past values, as well as the predicted indices. This density prediction filter extrapolates the recent (last ~27 days) behavior of the time series of the DCA density correction coefficients. The behavior is deduced through discrete Fourier transform of the frequency, phase, and amplitude of the coefficients as well as discrete wavelet transform to predict the transient part of the signal. The behavior of the coefficient time series is tied to the solar/geomagnetic heating indices. Therefore, the extrapolated time series is adjusted according to the values of the predicted indices. This prediction filter significantly increases the prediction accuracy of the HASDM thermospheric density model.

HASDM TEST PERIODS

The initial HASDM test period was the first 6 months of 2001. Observational data was collected from the entire SSN network on 75 calibration satellites and 50 evaluation satellites during this period. The data was then used to determine the optimum temperature coefficient set based on solution observability. The temperature field corrections were determined every 3 hours for this 6-month period, and then applied to the solution of individual trajectories of the evaluation (non-calibration) satellites to determine the accuracy of the temperature coefficients. Based on the greatly improved accuracy results obtained for this test period, a second full catalog test period was scheduled for a 2-month period in the summer of 2002. The purpose of this test was to apply the temperature corrections to the full drag catalog of satellites to demonstrate that HASDM can also be applied to satellites with normal levels of sensor tasking.

HASDM 2001 Test Period

The initial 6-month development test period started in January 2001. Seventy-five calibration satellites were selected for use in DCA, and approximately 50 evaluation satellites in addition to the calibration satellites were placed on high sensor tasking levels. Figure 1 shows the orbit distribution of the calibration satellites.

Height Min:	**190**	**250**	**300**	**400**	**500**	**600**	**700**
(km) Max:	**250**	**300**	**400**	**500**	**600**	**700**	**900**
Inclination:							
20-30	2	3	2				
30-40	5			2			
40-50	1		3	1	2	1	
50-60	1	1	1		1		
60-70				3			3
70-80		1	4	1			
80-100		2	6	6	13	6	4
Total	9	7	16	13	16	7	7

Figure 1. 2001 Calibration Satellite Orbits

The calibration set was selected based on obtaining a wide range of altitudes and inclinations. The first step in obtaining the time varying temperature coefficient field was to obtain "true" ballistic coefficients, B_{true}, for the majority of the calibration satellites. If the B_{true} values are not know then the unmodeled errors in density cannot be separated out from the fluctuations in the B_{model} values. Using satellite tracking data B_{true} values were obtained for over 40 satellites that were in orbit since 1970[1]. Differential orbit corrections were computed from 1970 to 2001 every 3 days throughout the 31-year period for each satellite. The B_{true} values were computed by averaging the nearly 3200 estimated B_{model} values obtained for each satellite. These B_{true} values were validated by comparing the B_{true} values of two spheres with theoretical values based on their known physical dimensions, and by comparing the B_{true} obtained for pairs of satellites having very similar size, shape, and mass.

B_{true} values were also computed for a number of low inclination satellites to be used for additional evaluation purposes. Differential orbit corrections were obtained for these satellites for the HASDM test period, and ratios of B_{model} to B_{true} values were obtained. The ratios are an indication of the unmodeled density variations occurring during the test period. Figure 2 shows the results from the set of low inclination evaluation satellites. The BTrue values are the B_{true} values computed over the 1970-2000 time period. Also plotted is the solar flux $F_{10.7}$ index. The period from day 1 to day 75 shows very little solar variability even though the $F_{10.7}$ value is still moderately high (~150). During this period of time, Jacchia's model atmosphere decreases more rapidly with altitude than the observed density. The higher the B_{model} / B_{true} ratio, the higher the true atmospheric density relative to the model density. When solar flux variability increases after day 75, the atmospheric density appears to be more consistent with the predicted model since the B_{model} variations are closer together. Thus, the initial HASDM 2001 time period appears to have a variety of atmospheric density variations to represent a large sampling of real world scenarios.

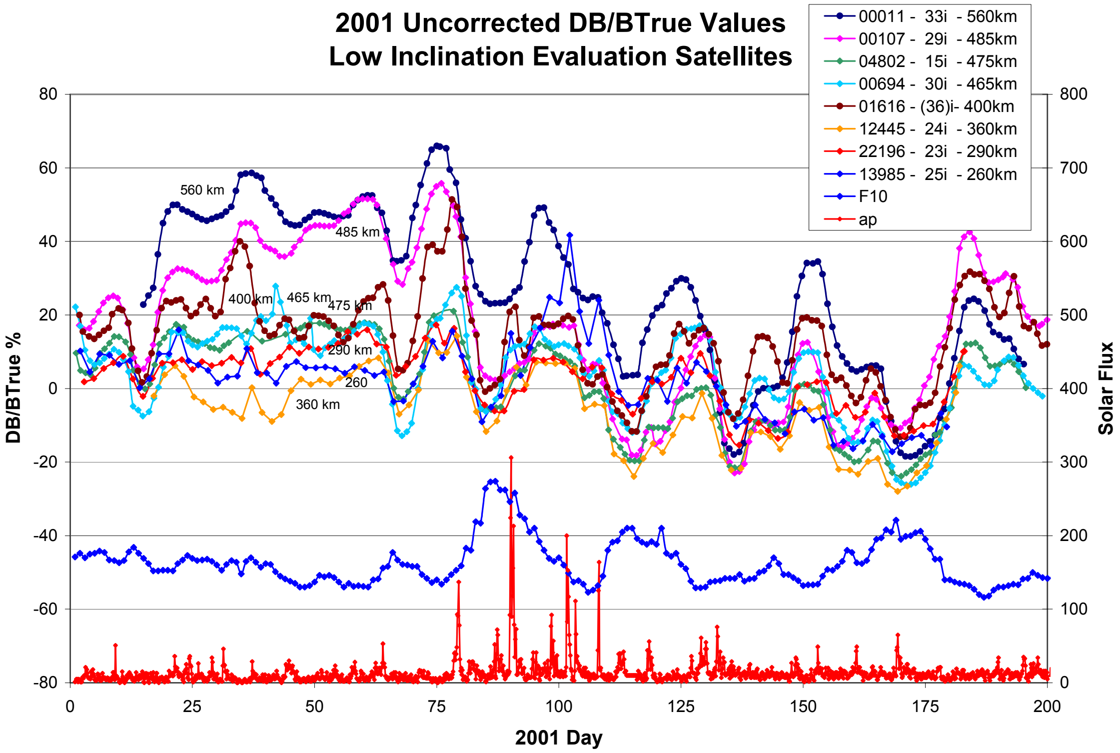

Figure 2. 2001 B/B_{true} Values

For the 6-month test period the temperature field was computed every 3 hours. This temperature field was then used in the HASDM thermospheric density model to recompute the B_{model} values for the calibration and evaluation satellites. If the temperature coefficients are correct then the B_{model} values should approach the B_{true} values throughout the test period. This indeed happened for almost all the satellites, with most having only a small variation remaining due to uncaptured local density variations. The root-mean-square of $(B_{model} - B_{true})/(B_{true})$ can be equated to a percentage error in the density field. These percentage density errors are plotted in Figure 3. The values are a 6 month average of the one sigma density error for each satellite. The calibration satellites show the best results, almost constant at 4% over the entire height range. This 4% error can be attributed to local density variations that are not captured with the low degree and order temperature spherical harmonics. The results for the evaluation satellites (plus the additional low inclination evaluation group) are slightly worse than the calibration satellites, with errors varying from 6 to 8% over the height range. This error is a good representation for all satellites for the real density error still remaining after the temperature field has been corrected by HASDM. It is interesting to note that without any correction the density errors range from 8% to 24% for high altitudes. This is a 1-sigma value, so the total density error can be above 50% at high altitudes. This is exactly what was found in Fig. 2, especially during the first half of the HASDM period when the B values grew in error the higher the altitude.

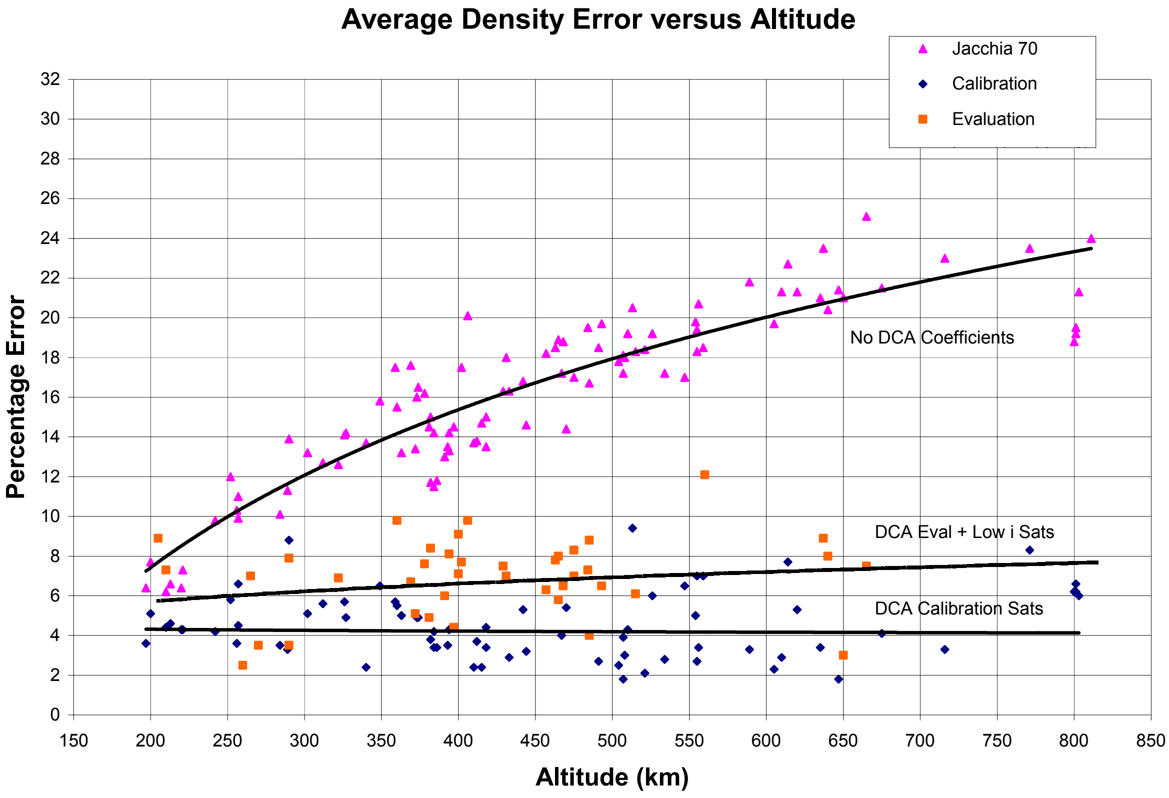

Figure 3. Density Errors

The HASDM results for this test are very good. The density error has been brought down to the 6-8% error level across all heights from 200 to 800 km. The temporal resolution has been reduced to 3-6 hours for the lower order variations, and approximately 18 hours for the higher order variations in the temperature/density field.

HASDM 2002 Test Period

The 2002 test period was a 2-month period starting in August 2002. The purpose of the test was to demonstrate the improvement in orbit fitting and prediction for the full drag regime catalog of satellites. The temperature field was computed every 3 hours over the test period using 80 calibration satellites. The temperature coefficients were then used in the density model for fitting over 5000 satellites in the drag regime. The results from this test period showed epoch/prediction position accuracies superior to the standard static model in all cases across the entire set of energy dissipation rate categories. The energy dissipation rate (EDR) is the rate at which atmospheric drag removes kinetic and potential energy from the satellite orbit. Improvement was shown for every prediction time past epoch for up to 72 hours. The epoch position error was reduced by a factor of approximately 1.7 for low EDR satellites, and by more than an order of magnitude for very high EDR satellites. The 72-hour prediction error across all EDRs was generally reduced by a factor of 1.5 to 2.0. These improvements even exceeded the predicted percentage increases expected from the original HASDM 2001 test period.

CONCLUSION

Current thermospheric density models do not adequately account for dynamic changes in atmospheric drag for orbit predictions, and no significant operational improvements have been made since 1970. Lack of progress is largely due to poor model inputs in the form of crude heating indices, as well as poor model accuracy and resolution, both spatial and temporal. The High Accuracy Satellite Drag Model (HASDM) initiative uses the Dynamic Calibration Atmosphere (DCA) algorithm to solve for thermospheric neutral density near real-time from the observed drag effects on a set of low-perigee inactive payloads and debris, referred to as *calibration satellites*. Many different calibration satellites with different orbits may be exploited to recover a dynamic global density field. The greater the number of calibration satellites, the better the accuracy. For this initiative, 75 to 80 such satellites were used.

HASDM's horizontally and temporally varying corrections produce a significant improvement in the accuracy of the density field. The estimated spherical harmonic coefficients may be readily used to specify and predict a corrected global density field, which can be applied to special perturbations orbit determination and prediction for any low-perigee satellite. Accuracy requirements for all Space Control missions should be met at a much better rate. This project, once operational, will also provide a useful neutral density database for basic research.

FUTURE DEVELOPMENTS

The initial operational implementation of HASDM is expected during the summer of 2004. At that time the temperature coefficients will be computed every 3 hours on a continuing basis, and the temperature field will be applied to computing daily orbit corrections and predictions for the entire satellite catalog in the drag regime. However, future improvements are already being planned for HASDM. An improvement in the static density base model used in HASDM will greatly help in long-term predictions. It is expected that better solar EUV indices ($E_{10.7}$, etc.) and geomagnetic storm indices will be developed to better characterize the heating input to the thermosphere. In addition, better correlations of density variations with solar indices will improve the long-term predictions. Another improvement expected for the future is an improvement in the prediction algorithm for the temperature field coefficients. Finally, it is contemplated that several hundred satellites could be used for calibration purposes, and thus increase the degree and order of the temperature field, which will decrease the unmodeled local density variations that currently exist.

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