Space Battlelab's High Accuracy Satellite Drag Model

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INTRODUCTION:

The High Accuracy Satellite Drag Model is a new initiative launched by the Air Force Space Battlelab in January 2001 to improve Air Force Space Command's ability to meet the stringent Space Surveillance Capstone Requirements for satellite trajectory prediction accuracy. For low perigee satellites, these requirements are not consistently met, largely because of current atmospheric density model errors of 15 to 20% [6]. This can affect missions like high-precision sensor acquisition of satellites, maneuver planning, re-entry predictions, collision avoidance and risk analysis. The Space Battlelab decided to fund this initiative because of the substantial pay-back expected, and the fact that it involves more risk than the acquisition community or operational community are willing to fund. It is also well suited to the Space Battlelab's project criteria of demonstrating unconventional ways of using existing data and technology to meet mission requirements and being able to demonstrate this in less than 18 months. Finally, this initiative leverages off an earlier Space Battlelab project[7] that demonstrated the promise the basic technique holds, even when only one satellite is used to determine the drag effects.

The initiative optimizes the earlier approach by simultaneously processing drag information from many satellite trajectories to solve for a high-resolution correction to the thermospheric density. Unlike the earlier effort, that used derived quantities from the orbit determination process, this initiative will directly process satellite tracking observations from the Space Surveillance Network.   It will determine the thermospheric density correction parameters, while solving for the states of the calibration satellites, in a single estimation process, known as the Dynamic Calibration Atmosphere (DCA).

This initiative will also capitalize on the new SOLAR2000 model developed for the Space Environment Center[12]. This is the first ever full solar spectrum model and acts like a data fusion engine, assimilating many different sources of solar irradiance data. It can generate many products related to the sun's electromagnetic radiation output. However, for this initiative, the extreme ultraviolet (EUV) band of radiation is of paramount importance. This radiation is the major heat source in the thermosphere, causing the atmospheric density to change up to 2 orders of magnitude, throughout the 11-year solar cycle[5]. SOLAR2000 will be modified to produce a 3-day prediction of the EUV radiation in the form of an effective $F_{10.7}$ index based on the intensity of this radiation. This new index is known as $E_{10.7}$, and when input to existing models requiring $F_{10.7}$, automatically boosts their accuracy performance.

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This project also includes the development of a prediction function that maps the time-history of solar and geomagnetic indices (including $E_{10.7}$) to the density correction parameters DCA estimates. DCA's high-resolution thermospheric density correction, together with the 3-day index prediction that maps to a corresponding density correction prediction, should significantly improve space control operations.

BACKGROUND

The goal of this initiative is to estimate an accurate correction to the modeled thermospheric neutral density using drag effect information from the trajectories of inactive satellites and orbiting debris. The greater the thermospheric density, the faster low earth orbit (LEO) objects spiral inward. Within the Air Force, the concept of estimating thermospheric density from satellite trajectories was first explored in 1995 at Air Force Space Command and Air Force Research Laboratory using Small Business Innovative Research funds. This led to the earlier Space Battlelab initiative, the Modified Atmospheric Density Model (MADM)[7], completed in March 2000.

In MADM, the main parameter used to determine the density is 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 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. 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:

$$a_{\text{D}} = 1/2\ B_{\text{true}}\ \rho_{\text{true}}\ V^2 \tag{1}$$

The true density ρ_{true} is generally not known, so the 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 in comparison 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}. The "observed" drag acceleration a_{D} has nearly the same value, regardless of the value of the modeled density ρ_{model} and B_{model}. Therefore,

$$a_{\text{D}} = 1/2\ B_{\text{model}}\ \rho_{\text{model}}\ V^2 \tag{2}$$

This implies that $B_{\text{true}}\ \rho_{\text{true}} = B_{\text{model}}\ \rho_{\text{model}}$ and that $\rho_{\text{true}} = (B_{\text{model}}/B_{\text{true}})\ \rho_{\text{model}}$. The ratio $B_{\text{model}}/B_{\text{true}}$ is referred to as the "scaled" estimated ballistic coefficient B_{scale}. Figure 1 shows that LEO satellites with different orbits generally exhibit similar trends in their B_{scale} histories. This indicates that B_{scale} can be used to correct the model density globally to obtain a rough estimate of the true density[10]. Once a value for B_{true} is estimated by averaging many successive values of B_{model}, then the value for ρ_{true} may be computed. MADM exploited this information from a single calibration satellite to deduce the bias of the model atmosphere. Since MADM used only one satellite, it produced modest results.

It reduced the rms of the fit span error by about 20% and reduced the error growth rate by about 10% for a 1-day prediction.
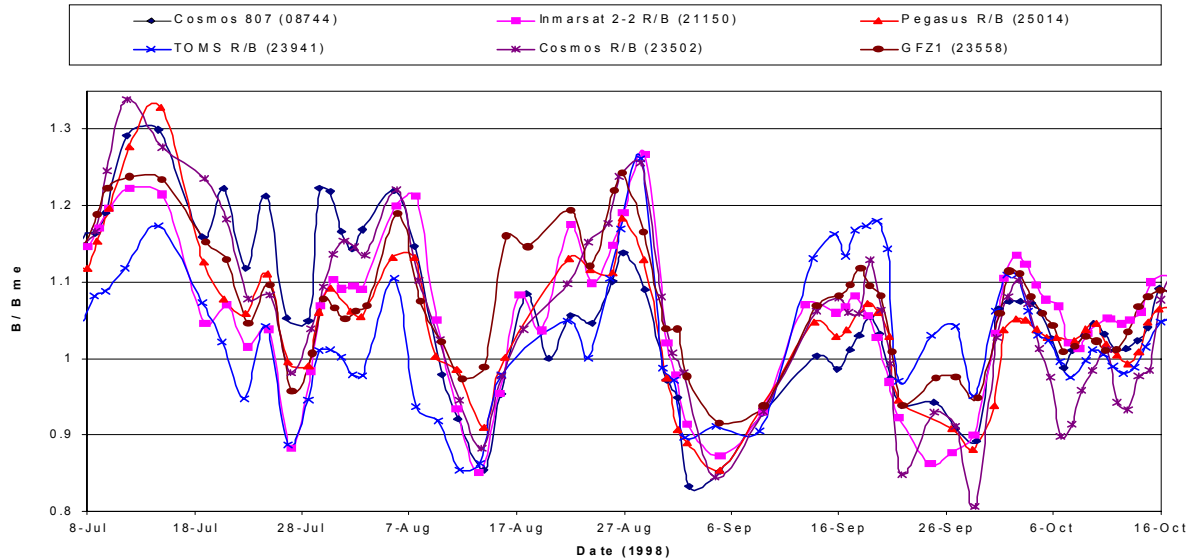

Figure 1. Scaled Ballistic Coefficient Histories ($B_{scale} = B_{model} / B_{true}$)

DYNAMIC CALIBRATION ATMOSPHERE

MADM employed a separate orbit determination process and a separate density estimation process. In the 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 solves for global density corrections and individual satellite state vectors. DCA uses Space Surveillance Network (SSN) observations directly, thus avoiding any intermediate step of fitting the density correction to estimated ballistic coefficient histories. This approach also optimizes use of the detailed information contained in the original space surveillance observations. As in MADM, DCA uses the Jacchia 1970 thermosphere as its base model[3]. While MADM only corrected two global temperature parameters of the base model, DCA will estimate up to 32 density correction parameters. This high-resolution correction will not only reduce the errors in the state error covariance for every low perigee satellite, but will also make these errors more realistic. In addition, the current operational sensitivity of orbit accuracy to the fit span length will be significantly reduced. Once these density correction parameters are computed, they will be output to a file so they can be accessed by users to improve orbit determination and prediction for all low perigee satellites. DCA is being developed by Omitron, Inc. in Colorado Springs, Colorado.

An important feature of DCA is its segmented solution approach. Although the state vector of each calibration satellite is solved for an entire ~3-day fit span interval, the density correction parameters will be solved on 3 to 6-hour sub-intervals within the fit span. This approach is used to extract the time resolution in the density correction needed to accurately estimate the dynamically changing thermospheric density[1]. This is especially important during geomagnetic storms. The observability for the parameters

estimated for each segment is expected to be good because of the large number (~60) of calibration satellites used, and because space surveillance tasking was increased to every pass with 10 observations each.

Figures 2 and 3 demonstrate the kind of accuracy improvement one can expect from this segmented approach. Figure 2 shows the in-track residuals for a satellite resulting from a 5-day fit. The fit span and prediction span are separated by the solid vertical line. Figure 3 shows the same 5-day fit span after a 12-hour segmented approach is applied. Here, the estimated ballistic coefficient is the parameter whose solution is segmented. We can expect a similar improvement, when instead, we segment the solution of a set of global density correction parameters and hold the estimate for the true ballistic coefficient fixed.
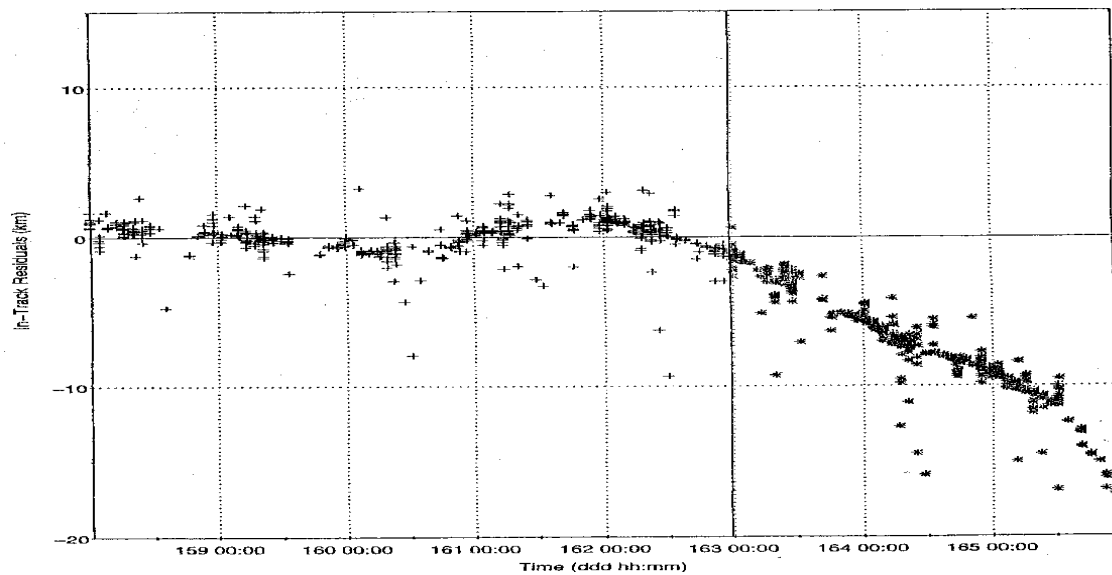

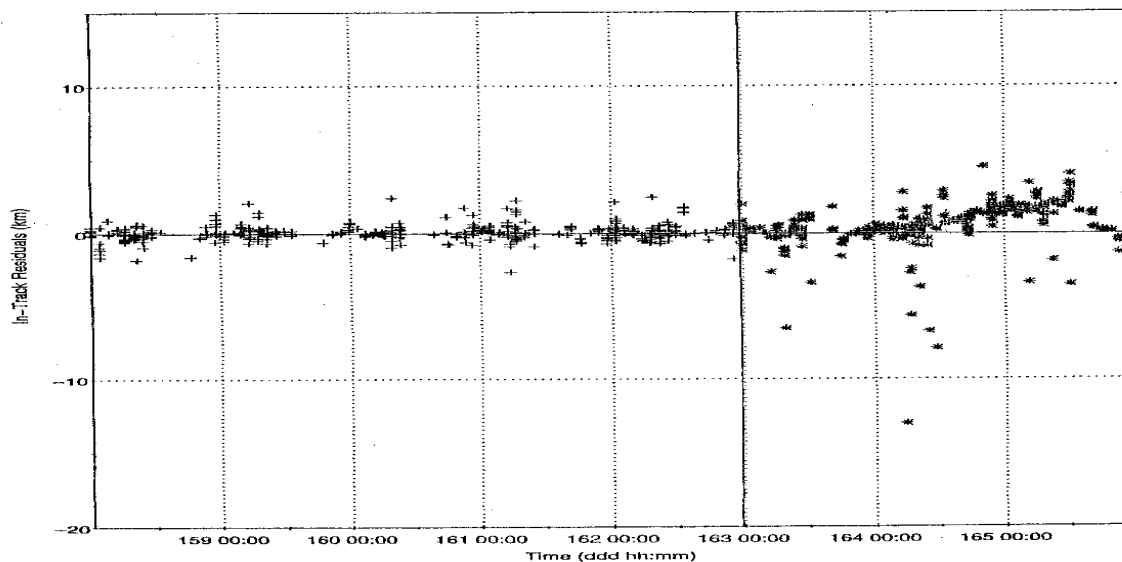Figure 2. In-Track Residuals for Satellite 1844 (5-Day Fit / 3-Day Prediction)

Figure 3. In-Track Residuals for Satellite 1844 (5-Day Segmented Fit / 3-Day Prediction)

TEMPERATURE PROFILES

For this initiative, about 60 calibration satellites are being used simultaneously to solve for a high-resolution density correction field. This correction field will correct two local parameters in the vertical temperature profile leading to a unique density profile. These correction parameters will each be expanded using a spherical harmonic series up to degree 3. The goal is to estimate a new set of coefficients for every 3-hour interval. The number of coefficients for a single spherical harmonic expansion to degree = 3 is 16 = $(3 + 1)^2$. Since there is an independent expansion for each of the two local temperature parameters, there are $2 \times 16 = 32$ parameters initially planned for DCA. After optimization of this parameter set, the level of truncation may change with a corresponding change in the number of parameters.

The two local temperature parameters in the correction are the so-called "inflection point temperature" T_x at 125 km altitude, and the exospheric temperature T_∞, the asymptotic temperature the profile approaches with increased altitude in the exosphere (>600 km altitude). The local values for T_x and T_∞ are both corrected indirectly through a global parameter know 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[3], and is given by the following expression:

$$T_c = 383.0 + 3.32\ F_{10.7} + 1.8(F_{10.7} - \overline{F}_{10.7}) \tag{3}$$

In the modified Jacchia 1970 model developed by the Space Warfare Center, a correction ΔT_c is added to the standard T_c value to produce a corrected value T'_c. The local exospheric temperature T_∞ is obtained from $T'_c = T_c + \Delta T_c$ by multiplying by the diurnal variation factor (a function of solar declination, latitude and local solar time), and then adding the contributions to T_∞ due to geomagnetic activity and the semiannual variation. In turn, the local value for T_x is computed from the local exospheric temperature T_∞ using the standard Jacchia 1970 expression:

$$T_x = 444.3807 + 0.02385\ T_\infty - 392.8292\ \exp(-\ 0.0021357\ T_\infty) \tag{4}$$

In this modified Jacchia model, local exospheric temperature T_x is further corrected by adding a direct ΔT_x correction to this empirical function to produce a corrected value $T'_x = T_x + \Delta T_x$. Both ΔT_c and ΔT_x are expressed in terms of independent spherical harmonic expansions in latitude and local solar time. Since local solar time is equivalent to the right ascension relative to the antisolar point, it is better to regard it as an angular coordinate than a time.

When $\Delta T_x = 0$, the temperature profile is identical a standard Jacchia 1970 profile for a given exospheric temperature. Figure 4 shows seven such temperature profiles, each corresponding to a different local exospheric temperature T_∞. These exospheric temperatures vary from 500 to 2000°K, representing the natural range of values. All temperature profiles start from a constant temperature of 183°K at 90 km altitude, the

lower boundary. The temperature increases with altitude, exhibiting an inflection point at a fixed altitude of 125 km, indicated in Figure 4 by the solid black vertical line. The temperature continues to increase and becomes asymptotic to the local exospheric temperature T_∞.
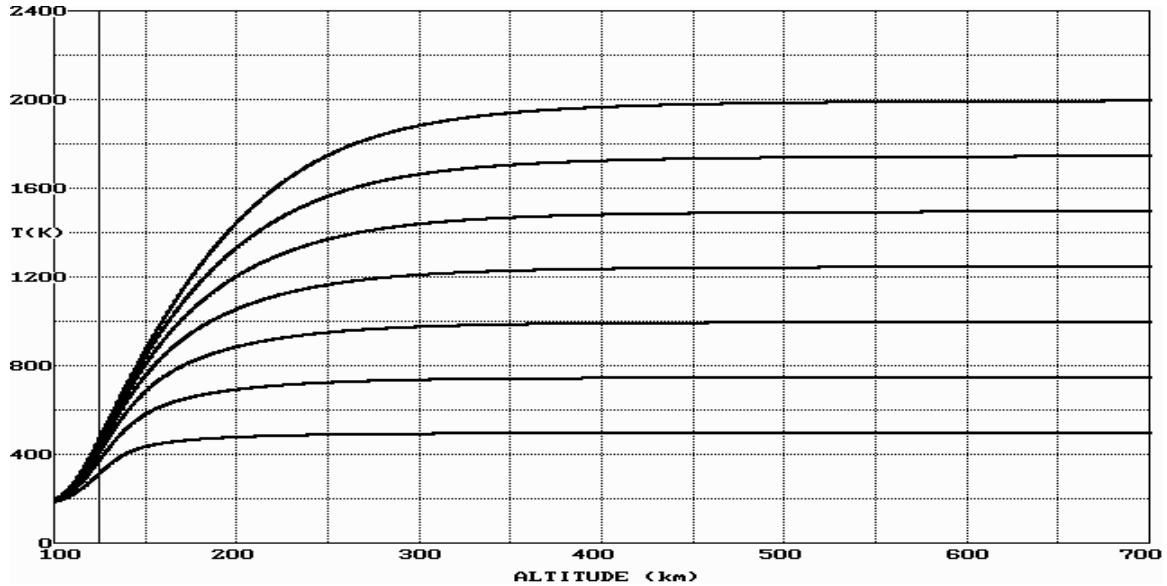

Figure 4. Temperature Profiles (T_∞ = 500, 750, 1000, 1250, 1500, 1750, 2000°K with ΔT_x = 0)

In the modified thermospheric model used for this initiative, the local inflection point temperature T_x is altered by a spherical harmonic correction ΔT_x. Figure 5 shows seven temperature profiles, each corresponding to a different T_x. The inflection point temperatures shown here range from 200 to 800°K. These T_x values occur along the solid black vertical line at an altitude of 125 km. To explore the effect of changing T_x only, the exospheric temperature in Figure 5 was held constant at T_∞ = 2000°K. Changing T_x acts to steepen or flatten the temperature gradient with altitude. For T_x values less than ~400°K, a second inflection point appears at altitudes above 125 km. As T_x decreases, this second inflection point dominates the one at 125 km. The local temperature profile leads to the local density profile through integration of the hydrostatic and diffusion equations[4].

SIMULATION OF ESTIMATION PROCESS

The Analysis and Engineering Division of the Space Warfare Center (SWC/AE) conducted a simulation demonstrating that a spherical harmonic density correction can be accurately recovered from trajectory information obtained from a separate orbit determination process[11]. The trajectory information consisted of a series of ephemeris points, the modeled density field used in the orbit determination, and long-term estimates of the true ballistic coefficient for many calibration satellites. From this information, energy dissipation rates (EDRs) were computed for these calibration satellites. This simulation is an extension of the original MADM concept; the differences being the use of EDRs instead of the scaled estimated ballistic coefficients (B_{scale}) as the input and the

use of multiple calibration satellites to recover multiple spherical harmonic density correction coefficients. Simulation is a useful way to validate the performance of an estimation algorithm when little real-world data is available. Measured thermospheric densities have been available only when satellite experiments designed to measure
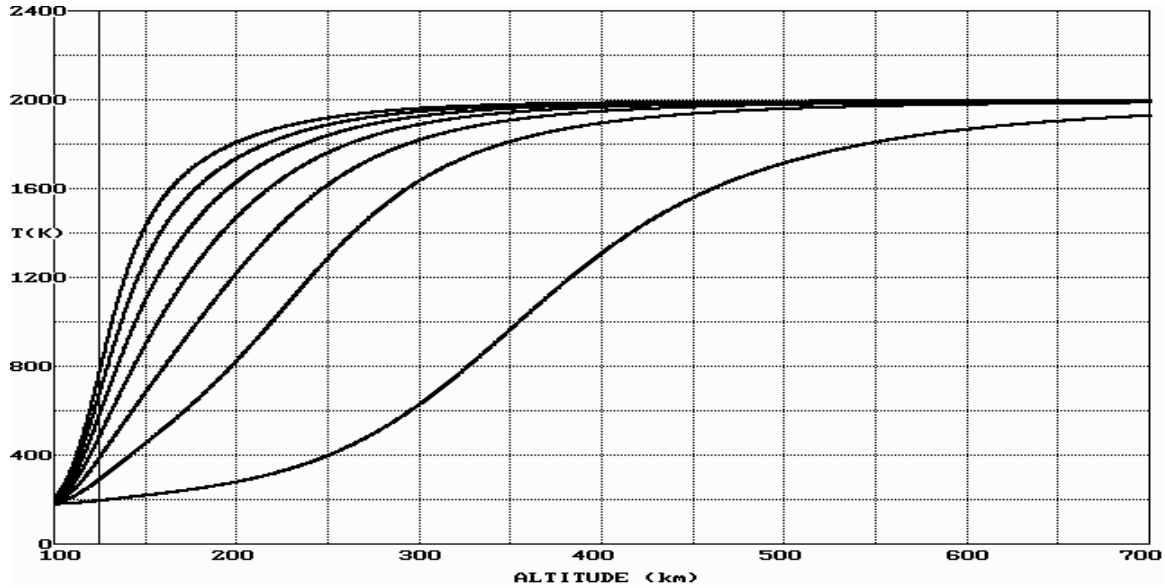

Figure 5. Temperature Profiles (T_x = 200, 300, 400, 500, 600, 700, 800°K with T_∞ = 2000°K)

density were active. The simulated density field was defined in terms of a spherical harmonic expansion of ΔT_c, the correction to the nighttime minimum exospheric temperature. The expansion was expressed as a function of latitude and local solar time. The calibration satellite orbits were also simulated by randomly choosing orbital elements within a useful range of values. The following list outlines how this was done:

- Random Perigee Location (in right ascension and declination)
- Random Perigee Altitudes (from 200 km to 500 km)
- Random Eccentricities (from 0 to 0.1)
- Random Inclinations (from 25° to 105°)
- Random (true) Ballistic Coefficients (from 0.0001 to 0.1 m^2/kg)

The energy dissipation rates (EDRs) were made more realistic by adding a Gaussian random deviate to the precise simulated value. The standard deviation of this introduced error was σ = 1 cm^2/sec^3, which is approximately the value of the EDR for satellites with EDRs just barely large enough to be useful for atmospheric calibration. Figure 6 demonstrates the estimation accuracy that can be obtained from the EDRs of 18 calibration satellites randomly chosen according to the criteria described above. At 400 km, the σ_T = 7.5° estimation error for temperature is equivalent to a σ_ρ = 3.1% error in density. When the number of satellites is increased to 36, the density error decreased to 0.4%. Figure 7 shows the truth temperature field.
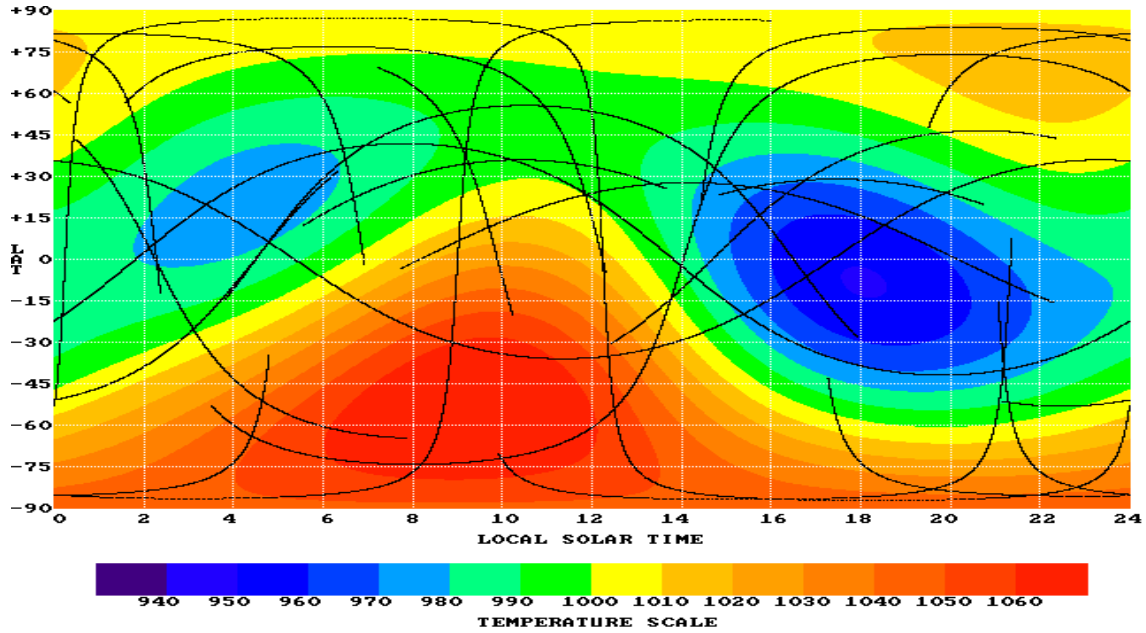
Figure 6. Nighttime Minimum Exospheric Temperature Estimated from 18 Satellites
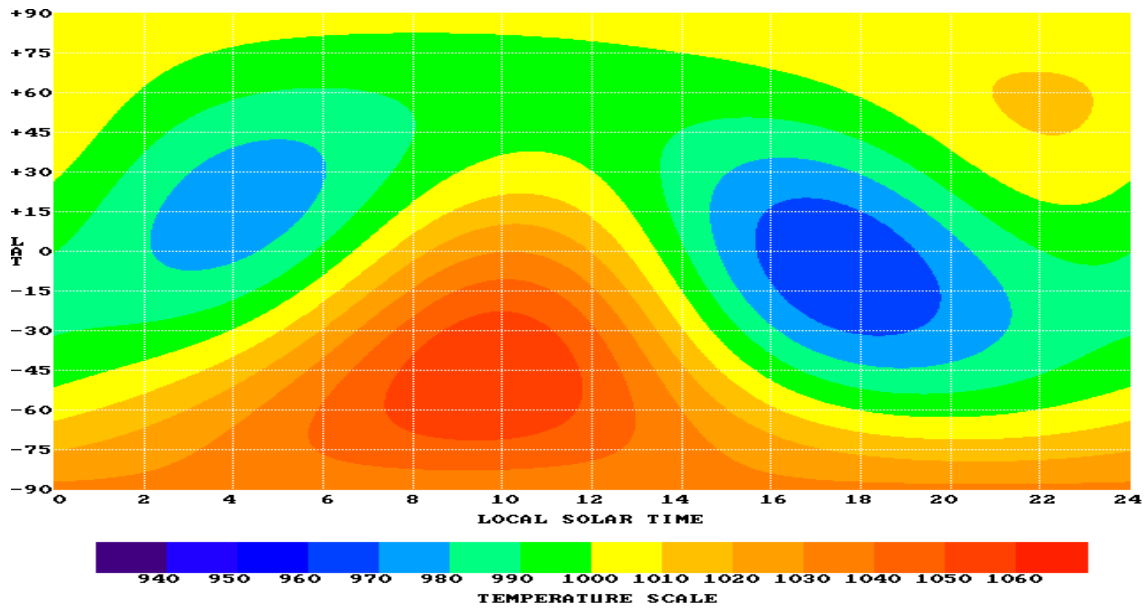($\sigma_T = 7.5° \Rightarrow \sigma_\rho = 3.1\%$ at 400 km altitude)

Figure 7. Nighttime Minimum Exospheric Temperature (Truth Data)

DENSITY PREDICTION TECHNIQUE

We will make use of the 3-day prediction of a_p as well as a 3-day prediction of $E_{10.7}$, produced by the SOLAR200 Solar Irradiance Model. This model is being developed by Federal Data Corporation for the Space Environment Center and other agencies.   SOLAR2000 is the first ever empirical full solar spectrum model. Its spectral resolution is 1 nm and extends from X-rays through the IR spectrum[12]. The temporal resolution extends from minutes to a full solar cycle (~11 years). It acts like a data fusion engine and ingests data from UV and EUV sensors, ground-based optical sensors and total irradiance sensors and imagers.   For the High Accuracy Satellite Drag Model, we

will use the SOLAR2000's $E_{10.7}$ index. This index is based on the total solar irradiance integrated over all extreme ultraviolet (EUV) wavelengths and is integrated in time over the past 24 hours. The resulting EUV flux was plotted versus the simultaneous $F_{10.7}$ indices and a curve was fit to the points. This curve is then used to translate the integrated EUV flux to the $E_{10.7}$ index. A similar procedure is being used to generate an $E_{10.7}$ corresponding to the 3-month mean of the $F_{10.7}$ index. When $E_{10.7}$ is used instead of $F_{10.7}$, it automatically increases the accuracy of the thermospheric density model, even if that model was constructed using the $F_{10.7}$ index. Currently, SOLAR2000 produces a now-cast of the $E_{10.7}$ index. A 3-day prediction of this index is expected to be ready by July 2001.

The density correction coefficients from the Dynamic Calibration Atmosphere (DCA) will be predicted out 3 days into the future using a mapping that relates the $E_{10.7}$ history and the geomagnetic index a_p history to these coefficients. All of the coefficients estimated by DCA will be expressed as a separate function of the time history of the past indices. Federal Data Corporation is tasked to develop this mapping for the Space Battlelab initiative. They plan to explore using a finite input response (FIR) filter or an artificial neural network. Once this mapping is developed, it will be applied in the same way to the indices predicted out 3 days to generate a 3-day prediction for density. In this way, we can leverage off the existing space forecast expertise in predicting the indices.

LABORATORY ASSISTANCE

Both Air Force Research Laboratory (AFRL) and Naval Research Laboratory (NRL) are participating in this project. Air Force Research Laboratory will validate the new $E_{10.7}$ index over one solar cycle. AFRL will also develop a means of isolating the semiannual variation from the spherical harmonic coefficients estimated by DCA. Although the semiannual variation is a slowly varying effect, it is highly variable from year to year. Isolating this variation from the spherical harmonic coefficients will prevent this variation from "polluting" the prediction mapping being developed by Federal Data Corporation. AFRL will validate this mapping by comparing the spherical harmonic coefficients produced by the mapping to the actual coefficients estimated by DCA.

Naval Research Laboratory will compare the density field estimated by DCA to the density field produced by their MSIS2000 model [2,9]. This model is designed to injest data from the new Special Sensor Ultraviolet Limb Imager (SSULI). This is a space-based airglow sensor that measures ultraviolet emissions from the thermosphere and ionosphere to deduce densities of individual neutral and ion gas species. The MSIS2000 model is then adjusted to these measurements, thus producing total neutral density. Any discrepancies between DCA and MSIS2000 will be analyzed and the models will be adjusted as appropriate. This will pave the way for a possible thermospheric density data fusion effort.

CONCLUSION

Atmospheric density models for computing drag forces on satellites can be a major source of inaccurate trajectory predictions for low perigee satellites. This deficiency can result in serious errors in the predicted position of satellites, especially those orbiting below 600 km altitude, the region known as the thermosphere. Many of these objects are of high interest to the Space Control mission.

Current thermospheric density models do not account for dynamic changes in atmospheric drag in orbit predictions, and no significant 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 resolution (both in space and time). The High Accuracy Satellite Drag Model initiative will use the Dynamic Calibration Atmosphere (DCA) algorithm that solves for the thermospheric density near real-time from the "observed" drag effects on a set of Low Earth Orbit (LEO) calibration satellites. The greater the thermospheric density, the greater the drag force on the calibration satellites. Many different calibration satellites with different orbits may be exploited to recover a high resolution, high accuracy density field. The greater the number of calibration satellites, the greater the density accuracy. For this initiative, we are using about 60 of these satellites, which consist of inactive satellites and debris objects. There are three innovations within this initiative that should improve the way satellite drag is determined and predicted:

- Dynamic Calibration Atmosphere (DCA) - This algorithm will determine a high accuracy, high resolution density correction from which we expect to model the true density to within a few percent. It will estimate this density every 3 to 6 hours.

- Mapping of Heating Indices to DCA Corrections - For this initiative, we will apply a detailed mapping from the solar/geomagnetic heating indices to the density correction parameters estimated by DCA. Applying the index-to-correction mapping to the predicted indices will automatically predict a high accuracy density correction. This mapping should significantly boost the prediction accuracy of the existing thermospheric model in response to predicted indices.

- New EUV Index ($E_{10.7}$) - This index is being generated by the new SOLAR2000 model, the first full spectrum model of solar electromagnetic radiation. Not only does this index better represent the true heating of the thermosphere due to solar extreme ultraviolet (EUV) radiation, but it also has the potential of being more accurately predicted out 3 days or more.

Based on the success of previous efforts using spherically symmetric density corrections[7,8], this spatially and temporally varying correction should produce a significantly more accurate density solution. The estimated spherical harmonic coefficients will 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 than what we see for current operations.

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