Comparison Of Atmospheric Density Models in the Thermospheric Region: MSIS-86 and DTM-78

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Abstract:

The German Satellite CHAMP (Challenging Minisatellite Payload) has the unique ability to measure the surface forces present. The total density can be easily derived from this measurement, with the help of models of solar radiation pressure and Earth’s albedo. This total density will be compared with the total density from two models, MSIS-86 (Hedin, 1987) and DTM-78 (Barlier et al., 1977). The total density from the CHAMP satellite is derived assuming instrument biases can be accurately estimated and that upper atmospheric winds are negligible. Therefore, the noise on the instrument grows as a function of latitude and geomagnetic activity, both indicators of upper atmospheric winds. In conclusion, in order to better determine orbits in the future (without having an accelerometer onboard), an accurate wind model is needed for the Thermosphere.
Introduction:

Neutral gas density in the upper atmosphere has been studied extensively since the 1970’s. One of the largest objectives of these studies has been to improve precision orbit determination and prediction. Currently the largest error in orbit determination and prediction of low altitude satellites is the unknown effect of drag (Marcos et al., 2002). There are three main causes of this error. The largest error, and the one that is analyzed in this paper, is the effect of the unknown density of the atmosphere interacting with the surface of the satellite. The second source of error is the unknown wind velocity relative to the earth. The third, smaller source of error is the unknown interaction between the atmospheric gases and the surface of the satellite, quantified by the coefficient of drag, \( C_D \). Two models, MSIS (Mass Spectrometer and Incoherent Scatter) and DTM (Drag Temperature Model), were made to model density of the neutral gases in the upper atmospheric region known as the Thermosphere. The Thermosphere is the region of the atmosphere above ~100 km, characterized by an abundance of atomic oxygen. The Thermosphere is dominated by the solar EUV energy, exciting many molecules and atoms, as well as causing photodissociation of oxygen (Tascione, 1994). Many geodetic satellites are inserted into orbits in the middle of this region because the proximity to the earth’s surface makes it easy to observe many things. However, having an orbit lower than this can require the satellite to carry more fuel to compete with the orbit decaying effect of the increased atmospheric density.

To compare the two models mentioned above, a case study was done on May 20th, 2001, using the German Satellite CHAMP as the satellite experiencing the changes in density. The CHAMP satellite has the unique capability to be able to compare these models to a total density measurement made by its onboard accelerometer. For this comparison, the MSIS-86 (Hedin, 1987) and DTM-78 (Barlier et al., 1977) models were used (number corresponds to the year that it was published). The trajectory of the CHAMP Satellite is shown in figure 1 for the 14-hour period.

Figure 1: Trajectory of CHAMP

CHAMP Satellite Mission:

The German satellite CHAMP, also known as the Challenging Mini-Satellite Payload, was launched into orbit on July 15th, 2000. The project plans to have a five-year duration to study geophysical properties of the Earth. With a near polar inclination, the satellite is able to study most of the Earth’s surface at an approximate altitude of 450 km approximately every 30 days. The main goal of the mission is to precisely studying the
gravity field of earth. Other goals of the project include studying the magnetic field of
the earth, and the atmospheric and ionospheric profile of the earth.

Prior to this mission, a fair amount was known about the gravity field of earth. Previous
research groups, working mostly with satellite-tracking data, have completed Earth
gravity field modeling in the past, as satellite-tracking data gives the best insight
into global gravity field perturbations. The basis behind these missions is to analyze the
perturbations of the orbit of a satellite. By accounting for non-conservative forces using
accurate models, one can estimate the accelerations on the satellite caused by
abnormalities in the gravity field. The CHAMP mission is conceptually similar to these
previous missions. However, the CHAMP mission combines the previous method with a
new combination of instruments that actually measures all of the non-conservative forces.
Replacing the previously modeled non-conservative forces with an actual measured value
reduces the error to the computed gravity field, assuming that this new instrumentation is
very precise.

The current research project focuses on using the accelerometer as the main
source of data, as opposed to just subtracting its affect to find gravitational forces. By
using the accelerometer data as the sum of all of the non-conservative forces present on
the surface of the satellite, the accelerometer can tell us very interesting things about the
density of the atmosphere. This method still depends on the quality of solar radiation
models as well as Earth albedo models when separating the forces that are causing a
signal on the accelerometer. Equally important, is the atmospheric model used to correct
biases on the accelerometer data.

The accelerometer being used in the CHAMP mission is a three-axis
accelerometer that controls the position of a test mass by using an electrical capacitance
force. The amount of force required to keep the test mass in a certain position relative to
the direction of each axis is measured, thus providing an accurate estimate of the non-
conservative forces acting on the outside of the spacecraft. The accelerometer for
CHAMP is provided by the French company Onera.

Method for Using Models MSIS-86 and DTM-78:

While making use of two different sets of data, both the MSIS-86 and the DTM-
78 models operate in approximately the same fashion. Both use the property of diffusion
to propagate a reference concentration of each type of molecule or atom, $c_i(120 \ km)$,
upwards, as shown by the function $f_i(z)$ in equation 1 and 2, where $\zeta$ is the geo-potential
altitude (Berger et al., 1998). The effect of altitude on density can be seen in figure 2 for
a solar quiet day, and a solar noisy day (Bruinsma et al., 1999).
The function $G_i(L)$, equation 3, controls the effects of the non-periodic (NP), periodic annual (PA), periodic semiannual (PSA), periodic diurnal (PD), periodic semidiurnal (PSD), and periodic terdiurnal (PTD) modeled terms. These terms are modeled by empirical coefficients, $a_i$, and estimated using a least squares method.

$$\rho(z) = \sum_i \frac{m_i}{N_A} c_i (120 km) f_i(z) \exp(G_i(L))$$  \hspace{1cm} (eq. 1)

$$f_i(z) = \left(\frac{T_{120}}{T(z)}\right)^{1+\alpha_i} \exp(-\zeta \gamma_i)$$  \hspace{1cm} (eq. 2)

$$G(L) = \sum_i a_i NP + \sum_j a_j NP + \sum_k a_k NP + \sum_m a_m NP + \sum_n a_n NP$$  \hspace{1cm} (eq. 3)

The Geodyn II program, was written and is used exclusively at the Goddard Space Flight Center. Geodyn is a precision orbit determination program, which can be configured to use a number of atmospheric density models, solar radiation pressure models, and Earth albedo models. The option of replacing these models with accelerometry data also makes Geodyn useful in estimating Earth’s gravity field. By slightly modifying the Geodyn program, a dedicated file was created with in-situ total density, drag acceleration, solar radiation pressure, and Earth albedo acceleration output. The Geodyn program takes into account the complex surface of the satellite, using a 15-plate model to calculate the coefficient of drag, $C_D$, and the effective area of the satellite. This was done twice, once for each atmospheric model. The two models are then compared alongside different parameters such as latitude, longitude, and local time.
Method for Deriving CHAMP Total Density:

Once the predicted data is acquired using the Geodyn II program, total density from CHAMP can then be analyzed. This calculation can be done quite easily by noticing a few similarities between the model and accelerometer data. Both models and the accelerometer data follow the relationship in equation 4, relating drag to density. Considering that the coefficient of drag, $C_D$, the effective area, $A$, mass of the satellite, $m$, and the velocity with respect to the earth, $v$, don’t change depending on the model that is used, total densities derived by each model can be related to any other model by equation 6.

$$\ddot{a}_D = -\frac{1}{2} C_D \frac{A}{m} \rho \|v\| \ddot{v}$$  \hspace{1cm} (eq. 4)

$$\frac{\ddot{a}_{D,MSIS}}{\rho_{MSIS}} = -\frac{1}{2} C_D \frac{A}{m} \|v\| \ddot{v} = \frac{\ddot{a}_{D,CHAMP}}{\rho_{CHAMP}}$$  \hspace{1cm} (eq. 5)

$$\rho_{CHAMP} = \rho_{MSIS} \frac{a_{D,CHAMP}}{a_{D,MSIS}}$$  \hspace{1cm} (eq. 6)

The next step is to estimate the contribution of drag measured by the accelerometer by subtracting the effects of solar radiation pressure and Earth’s albedo. These two accelerations are given at each epoch, in the data file created by Geodyn. Doing this, equation 6 becomes:

$$\rho_{CHAMP} = \frac{a_{CHAMP} - a_{SRP} - a_{EA}}{a_{D,MSIS}} \rho_{MSIS}$$  \hspace{1cm} (eq. 7)

where the modeled accelerations are along the velocity vector, and $a_{CHAMP}$ is the component of the measured acceleration along the velocity vector (Bruinsma et al., 2003).

Error Analysis:

Most of the error in deriving total densities from CHAMP accelerometry is caused by the biases of the instrument. Due to the extremely difficult nature of calibrating the instrument, these biases have to be estimated in-situ. For this case study, the estimated bias was $-3.29 \times 10^{-6}$ m/s², with a scale factor of 0.932. The exact uncertainty of this measurement is hard to determine, but is believed to be about 10%.

Estimating the coefficient of drag, $C_D$, is also an area of concern. However, for this comparison, this coefficient is assumed to be the same for each model. Therefore, it won’t have an effect on the CHAMP accelerometry relative to the other two models being looked at.
The geomagnetic activity is also to blame for many the noise on the Accelerometer data. When geomagnetic activity is high, atmospheric winds at the poles cause a breakdown in the density modeling. Overall, the noise on the total density derived from the CHAMP accelerometer is on the order of 15-25%, depending on the geomagnetic activity (Bruinsma et al., 2003).
Results:

The resulting data from both atmospheric models is presented in a way that is not altogether straightforward. When analyzing total of the atmosphere for a given satellite, factors such as latitude, longitude, altitude, and local time are constantly changing. Each of these factors can have a drastic effect on the behavior of the model. Therefore, it is not enough to look at the models by themselves, but to compare them to the other factors. Figure 3 compares the behavior of the MSIS-86 and DTM-78 models over the 14-hour flight of the satellite while also showing the geodetic altitude of the satellite. Having a basic understanding of how altitude affects both models, the density should decrease with altitude. If altitude were the dominating effect, the density curve would look much like the negative of the altitude curve. However, that assumption is only true when observing density at a certain point above the Earth’s surface. As the satellite changes its position, the function $G_i(L)$ dominates both models, and there isn’t a strong relationship between the altitude and the density.

![Comparison of Modeled Density with Altitude](image)

Figure 3: MSIS-86 and DTM-78 models shown with geodetic altitude
One of the largest factors in the $G_L$ function that can be observed over a single day is local time. Because Solar EUV rays dominate most of the dynamics in the Thermosphere, the difference between daytime densities and nighttime densities can change quite a bit. Comparing the models to the solar local time, as in figure 4, gives a partial explanation for the increase of density with increasing altitude, that were observed in figure 3. Both models match each other fairly well at certain points in the orbit, for instance, as the density starts to decrease on each orbit, both models lie on top of each other. However, there are many places where the models have large differences. The segments of the orbit in which the density is at it’s maximum and at its minimum, are places where the two models don’t necessarily agree. These segments usually correspond to the steep increases in the solar local time curve. This means that the two models don’t agree as they pass over the Polar Regions (north pole for increasing solar local time from ~11 to ~23 hours).

![Comparison of Modeled Density with Solar Local Time](image_url)

Figure 4: MSIS-86 and DTM-78 models shown with solar local time
For the purpose of comparing CHAMP derived total densities, the MSIS-86 model is used. This is done because of the MSIS-86 model agrees more closely with the CHAMP derived densities. Figure 5 shows the MSIS-86 model and the total densities derived from the CHAMP accelerometer. The two models agree fairly well for densities below $2 \times 10^{-12}$ (kg/m$^3$). However, there are some discrepancies for densities above this limit.

![Figure 5: MSIS-86 model and CHAMP derived total densities](image-url)
The accelerometer data seems to get somewhat noisy around the poles, as can be seen in figure 6. In fact there are often large spikes in the CHAMP densities where there are none in the MSIS-86 model. This could be caused by the unknown affects that the Polar Regions have on atmospheric density. Another possibility is that the electrical system of the CHAMP satellite is adversely affected by the increased flux of charged particles in the Polar Region. Regardless of the cause, the spikes usually occur very close to the highest latitude that the satellite reaches. The spikes are not the only inconsistencies between the two data sets. As the latitude increases, large variations are seen between the MSIS-86 and the CHAMP derived total densities. These deviations happen at a slower much slower rate than the spikes, and the two models display their own unique behavior. This indicates, while the spikes might be caused by electrical problems, the behavior of the total atmospheric density is not well understood by the MSIS-86 model near the Polar Regions.

![Comparison of Densities with Latitude](image)

**Figure 6:** MSIS-86 model and CHAMP derived total densities shown with geodetic latitude

One feasible explanation for the difference between data sets at high latitudes could be caused by the fact that the MSIS-86 model is derived from data that does not largely represent the Polar Regions. Of all of the satellites with mass spectrometers that were used in deriving the MSIS-86 model, none that studied similar altitudes had Polar orbits. Table 1 shows the orbit specifications of the satellite used. Another problem is the representation of the Polar Regions with Incoherent Scatter stations. Building a
station that is capable of incoherent scatter measurements is very expensive; therefore, there were only about 6 such stations at the time. All of the stations at the time were located at middle to low latitudes, seen in table 2.

Table 1: MSIS-86 Mass Spectrometry Coverage

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Altitude (km)</th>
<th>Inclination (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGO-6</td>
<td>400-700</td>
<td>82</td>
</tr>
<tr>
<td>Aeros-A</td>
<td>200-500</td>
<td>83</td>
</tr>
<tr>
<td>AE-C</td>
<td>135-400</td>
<td>68.1</td>
</tr>
<tr>
<td>AE-D</td>
<td>140-400</td>
<td>90.1</td>
</tr>
<tr>
<td>AE-E</td>
<td>140-450</td>
<td>19.7</td>
</tr>
</tbody>
</table>

Table 2: MSIS-86 Incoherent Scatter Coverage

<table>
<thead>
<tr>
<th>IC Station</th>
<th>Latitude (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millstone Hill</td>
<td>42.6 N</td>
</tr>
<tr>
<td>Arecibo</td>
<td>18.3 N</td>
</tr>
<tr>
<td>St. Santin</td>
<td>44.6 N</td>
</tr>
<tr>
<td>Jicamarca</td>
<td>0.9 N</td>
</tr>
<tr>
<td>Malvern</td>
<td>52.1 N</td>
</tr>
</tbody>
</table>

Another feasible explanation is that the atmospheric winds are large enough to make our assumption of a co-rotating atmosphere invalid. In this case, the satellite velocity vector with respect to the earth doesn’t represent the velocity difference between the atmosphere and the satellite. This would cause the total density derived from CHAMP to be inaccurate. However, this same effect would cause the MSIS-86 model to be inaccurate when determining orbits.

Conclusions and Future Plans:

The MSIS-86 model proves to be a better estimate of total density than the DTM-78 model. However, both models display inadequacies in certain regions of the atmosphere. These inadequacies need to be studied using total density measurements, as well as other means. After correlations are made between the cause and effect, a new model should be derived. As the model improves, more will be learned about the dynamics of the Thermosphere, and precise orbit determination will be greatly improved. Also, in order to offset the effects of the atmospheric winds, the model needs to take into account wind patterns.
Many of the conclusions that can be drawn from the small case study of May 20th, 2001, are very qualitative in nature. However, in the upcoming months, the method outlined in this paper will be used to construct a large data set of total densities derived from the CHAMP accelerometer data. This data set will serve as a comparison to use when testing the validity of models such as the two seen here. This data set can also serve as a component of a larger data set that can be used to derive a new model for the Thermospheric region of the atmosphere (total density observations cannot be used by itself to derive a Thermospheric model without assuming that the atmosphere is made up of only one type of particle).

References:


