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The Effects of Density Model Phase Errors on Orbit Prediction

by

Christian Guignet

B.S., The Pennsylvania State University, 2009

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Master of Science

Department of Aerospace Engineering Sciences

2011

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This thesis entitled:
The Effects of Density Model Phase Errors on Orbit Prediction
written by Christian Guignet
has been approved for the Department of Aerospace Engineering Sciences

George Born

Jeffrey M. Forbes

R. Steven Nerem

Date ____________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Guignet, Christian (MS. Aerospace)

The Effects of Density Model Phase Errors on Orbit Prediction

Thesis directed by Dr. George Born

This thesis examines the effects of time shifts in density models and their effects on orbit prediction. Empirical density models are subject to lags in their prediction of atmospheric density, especially during times of high geomagnetic activity. An analytical density model is used to demonstrate that time delays can cause errors in the satellite orbit, and also that the errors can increase as satellite height decreases. The JB2008 and NRLMSISE-00 models are examined here. The models are first compared to densities that were derived from accelerometers on the CHAMP spacecraft. Satellite orbits are integrated using each of the models with the best available inputs and the CHAMP density. Errors resulting from the models are seen to reach up to several kilometers, with the JB2008 model performing the best. Time shifts are then introduced to the models, and they are each compared to a model with the best available inputs. The time shifts range from 1 to 6 hours. It is shown that errors increase for larger shifts, up to several kilometers again, with the NRLMSISE-00 model performing the best for the shifted densities. Finally shifts in real world density fluctations are examined by smoothing the CHAMP densities to remove short term orbital variations, and then shifting these densities by 1 to 6 hours. The errors shown in this case again reach several kilometers. The errors seen are shown to be significant to various spacecraft operations for all cases. The largest errors in all cases are also shown to occur during times of high geomagnetic activity.

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Dedication

To my family and friends for their support.

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Acknowledgements

I want to thank my advisor, Dr. George Born, for taking me on as a student and giving me the opportunity to conduct this research. I'd also like to thank Dr. Forbes and the neutral density MURI for providing the funding to work on this problem, as well as guiding the focus of my research. Finally, I want to thank Rodney Anderson for his previous contributions, as well as helping me to get started with my initial work.

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Chapter 1

Introduction and Motivation

Atmospheric density models have made significant improvements in their ability to predict densities. Improvement in models have thus advanced the quality of orbit predictions. As orbit predictions begin to require higher quality, the atmospheric density models must also be improved. In order to improve the density models, a natural question that arises is which area of the density model can benefit the most from new improvements. Quantifying these problems can allow researchers to identify the most problematic areas and focus there efforts on improving those areas of the model. Anderson, Born, and Forbes examined in a previous study examined the effects of various horizontal wavelengths in the atmosphere model on orbit predictions, using both theoretical models and actual satellite data.[1]This study showed that the spatial errors had did not have a significant effect on orbit prediction compared to time-delay errors. Thus, quantifying the effects of time delays on orbit prediction became the focus of this thesis.

Atmospheric models are typically sufficient at predicting densities in order to meet orbit prediction requirements. Certain cases can arise, though, in which the density prediction is not adequate to meet the needs of orbit prediction. One such case is during times of high geomagnetic activity. A 1972 study by Forbes showed the effects of time-delay errors on orbit prediction. In this study, the effects were studied on the orbit prediction of the DB-7 satellite. This figure shows that an early prediction of an increase in density by the Jachia model[13] causes an orbit error that is nearly equal to the error that would result from not predicting an increase at all. The density delays in this study are on the order of a quarter of day, which are not observed anymore. However,

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delays of approximately 1-6 hours can be observed now with current density models. These delays can create significant errors in orbit prediction which may be of importance for certain applications. The work performed here examines delays of this magnitude as well as early increases in density of the same magnitude.

When examining orbit prediction errors due to density time delays, it is important to have an idea of what magnitudes of orbit errors are of significant. Improving density models for orbit prediction has been an area of interest to the U.S. Air Force as well as others for many years.[2, 8, 7, 3, 4, 6, 10, 21]. The Air Force has provided some orbit error magnitudes of interest for this study, which are reproduced from Anderson et al. in Table 1.1.[5]These requirements list errors of relevance to the Air Force for different spacecraft altitudes.

Table 1.1: 24-hour orbit prediction errors of significance to the U.S. Air Force for several altitudes.

Altitude (km)	Error (m)
200	> 250
400	> 100
800	> 50

Orbit prediction errors due to density delays also have relevance to conjunction analysis. There are over 22,000 trackable objects on orbit, and the risk of collision requires that accurate analysis can be performed in order to assess this risk.[15, 11]Conjunction analysis quantifies the risk of collision of two satellites which are identified as having a close approach. In order to perform the analysis, state and uncertainty information for both satellites must be computed. For satellites in low Earth orbit, such as those studied here, the main driver of uncertainty is perturbations due to atmospheric drag.[12] During times of high geomagnetic activity, these perturbations have larger effects due to larger density variability.

To determine if analysis should be performed on a possible collision, NASA GSFC determines a safety volume about a spacecraft, and checks to see if another spacecraft will enter that volume.[15] There are several levels of concern for the safety volume. For the level of most concern, the Watch

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Volume, the stand-off radius is 1 km in the radial, in-track, and cross-track directions. A satellite within this volume would warrant a closer examination and a possible collision avoidance maneuver.

The risk of collision is usually quantified using the Probablity of Collision, P_c. This is reported for several miss distances. The paper by Frigm shows that during solar maximum, density variability causes P_c to be greater at larger miss distances. These miss distances are on the order of several hundred meters. Geomagnetic storms are more frequent and stronger during solar maximum, which means that density delays will be more common during this time. The orbit errors here could then have a large bearing on conjunction analysis.

Time delays in density prediction are looked at due to the fact that the atmospheric models studied here rely on measured parameters in order to predict the density. The predicted density can lag behind actual measured density because of sudden changes in these parameters that are not able to be predicted. In order to study this problem, statistical differences between two different atmospheric models as well as observed densities taken from satellite measurements are examined. The density measurements are taken from observations made by the Challenging Minisatellite Payload (CHAMP) satellite. The model densities are taken from two different models, the NRLMSISE-00 empirical model, as well as the JB2008 model. The models will be discussed in more detail in the next section.

1.1 Models

The focus of this research is to quantify the effects of density models on spacecraft in low Earth orbits. Thus, it was decided to use a two-body with J2 model for the spacecraft orbit integration. The acceleration due to drag is computed using the densities from one of the models or the CHAMP spacecraft. This was decided in order to focus on the time delays in the density model and eliminate the need to account for the effects of detailed gravity models.

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1.1.1 Two-Body Model with J2 and Drag

Acceleration due to gravity is given by

$$\ddot{\mathbf{r}} = \nabla U \tag{1.1}$$

where U is the gravitational potential with J2 and is

$$U = \frac{\mu}{r}[1 - J_2(\frac{R_{Earth}}{r})^2(\frac{3}{2}\frac{z}{r} - \frac{1}{2})] \tag{1.2}$$

where R_{Earth} is Earth's radius, r is the position of the spacecraft, and z is the z component of the position.

Acceleration due to drag (or force per unit mass) is

$$\bar{a}_{drag} = -\frac{1}{2}\left(\frac{C_d A}{m}\right)\rho V_a \bar{V}_a \tag{1.3}$$

where $m/(C_d A)$ is referred to as the ballistic coefficient. The velocity relative to the atmosphere may be computed as

$$\bar{V}_a = \begin{bmatrix} \dot{x} + \dot{\theta} y \\ \dot{y} - \dot{\theta} x \\ \dot{z} \end{bmatrix}. \tag{1.4}$$

In the paper by Anderson, Born, and Forbes[1], prograde, retrograde, and polar orbit cases were examined. The results of interest to this research varied little with orbit type, and as such the results here will always be generated using a polar orbit.

1.1.2 NRLMSISE-00 Model

One of the density models used in this research is the U.S. Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar (NRLMSISE-00) atmospheric density model.[17] This model is an update which improves upon the previous MSISE-90 model. In order to compute the density at a specific altitude, the model requires several inputs which include the position of the spacecraft (height, latitude, longitude), UTC time as well as local solar time, and several

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geomagnetic and solar indices. The indices used are the 8 daily 3 hour ap indices, as well at the $F_{10.7}$ solar flux for the previous day and an 81 day average of the $F_{10.7}$ flux for the current day. The ap indices will be discussed later as they relate to determining geomagnetic storms. The $F_{10.7}$ is a daily value, and as such will not have a large effect on this study since the time scales dealt with here are on the order of hours. Thus, the $F_{10.7}$ flux will rarely change. This study used past data from 2003 through 2008, so the indices used were known exactly. The accuracy of the model may change if it was necessary to predict the density in the future, as the values of the indices must also be predicted.

1.1.3 JB2008 Model

The other density model used is the Jacchia-Bowman 2008 (JB2008) model, which is an improved revision of the previous Jacchia-Bowman 2006 model. This model uses different indices than the NRLMSISE model, which include four solar and two geomagnetic indices. The solar indices include the $F_{10.7}$ index, which is the same as used in the NRLMSISE model, as well as the $S_{10.7}$, $M_{10.7}$, and $Y_{10.7}$. As with the $F_{10.7}$ flux values, these other solar indices are reported daily, and thus will not have an effect on the studies here. The geomagnetic indices used are the 3 hour ap indices as well as the Disturbance Time Index (Dst). The Dst index is used to indicate the strength of the ring current in the inner magnetosphere.[9] It is available on an hourly basis, as opposed to the three hour ap index. The model uses the ap value to compute the density if the ap value is less than 40. If it is over 40, a storm is assumed and the Dst index is used.[26]

1.2 CHAMP Spacecraft

The research performed here uses data collected from the CHAMP spacecraft. It was launched into its low Earth orbit on July 15, 2000 with an initial altitude of 454 km. It had a nearly polar orbit with an inclination of 87 degrees. The mass at launch was 522 kg, and dropped to approximately 505-507 kg in 2003, the year for which density data is first available. More information on the satellite can be found in Reigber et al.[20] and Kuang et al.[14]

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Chapter 2

Density Data

The data used in this study comes from three different sources, measured densities from the CHAMP satellite, and predicted data from the NRLMSISE-00 and JB2008 models. The CHAMP densities were obtained by processing measurements from the spacecraft's sensivive onboard accelerometer. The data was processed by Sutton at the University of Colorado, and more information on the process and application of the data can be found in Sutton et al.[23, 24, 25] as well as in Sutton's dissertation.[22] The measured density data is available from 2001 through 2008, and the work done here focuses on 2003 through 2008. The time span covers a period of higher solar activity in 2003 to quieter periods into 2008.

2.1 Storms in Data

In order to determine what kind of delays in the density prediction can be seen, several storms were examined. In order to determine what would constitute a geomagnetic storm, geomagnetic indices were examined. The K-index is a measurement used to quantify the disturbances in the horizontal component of Earth's magnetic field. K-index values are computed on a daily three-hour basis at several locations around the world. The planetary Kp index is computed through a weighted average of the K-index values from various observatories. The ap index, which is used in both of the density models, is a linear index related to the Kp index as shown by the scale in Table 2.1. The ap index is useful when sums and averages of daily activity are desired. See Prölss[19] for more information on Kp and ap as well as for a source of the values in Table 2.1.

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Table 2.1: Relationship between Kp and ap.

Kp	ap	Kp	ap
$0_\circ$	0	5.	39
0_+	2	$5_\circ$	48
1.	3	5_+	56
$1_\circ$	4	6.	67
1_+	5	$6_\circ$	80
2.	6	6_+	94
$2_\circ$	7	7.	111
2_+	9	$7_\circ$	132
3.	12	7_+	154
$3_\circ$	15	8.	179
3_+	18	$8_\circ$	207
4.	22	8_+	236
$4_\circ$	27	9.	300
4_+	32	$9_\circ$	400

Geomagnetic storms and their strengths can be classified by Kp value, with NOAA having five different classifications for a storm.[18] The storm classification begins at a Kp value of 5 and increases in severity as the Kp value rises, with 9 being the most intense storm. During active years, Kp values of 5 or greater can be quite common. In 2003, there were 103 days in which a Kp value of at least 5 was observed. More severe storms, as classified by a higher Kp value, are less common. A Kp value of 9 is observed only twice in the years studied, occurring during the same storm in 2003, which was the most active year. The number of storm days for the years 2004 through 2008 is significantly less, but a Kp value of 8 is still observed on nine days during that time period. Table 2.2 gives the precise number of days where each Kp value occurred throughout the studied years.

2.2 Time Delays in Data

Measuring the time delays in the model density for several storms provides an understanding of the types of time delays that may be expected and provides values to focus on for the remainder of this study. Sutton also provides some analysis of the data that gives an indication of the types of errors that might be expected for storms or other density increases. In order to get an idea of

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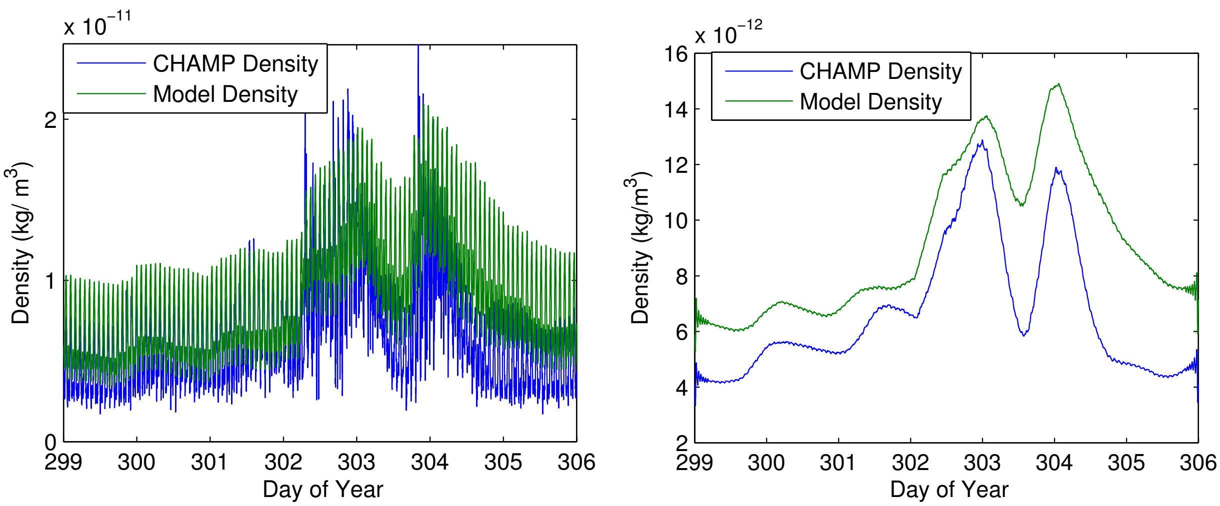
Table 2.2: Number of days that Kp exceeded the specified value each year.

	Kp Cutoff Values				
Year	5	6	7	8	9
2003	111	33	10	5	2
2004	33	17	9	6	0
2005	51	21	15	4	0
2006	28	8	3	1	0
2007	19	0	0	0	0
2008	11	2	0	0	0



(a) Actual Density

(b) Smoothed Density

Figure 2.1: October 29, 2003 plot showing actual density and smoothed density.

the types of time-delays that could be expected, the model densities were computed for days that had a Kp value of 5 or higher. The approximate time that the model density took to display a peak density was then compared to the time it took the CHAMP densities to show a peak. Model densities were computed using the position of the CHAMP satellite that was given by Sutton. In order to best determine where the peak densities occurred, the densities were smoothed using 701 points. This smoothing was done in order to remove orbital variations in the density. The peaks are then more obvious and the time delays can be determined. The CHAMP density is plotted along with the density obtained from the NRLMSISE-00 model in Figure 2.1(a) for the large storm in October of 2003, with the smoothed densities for this same storm shown in Figure 2.1(b).

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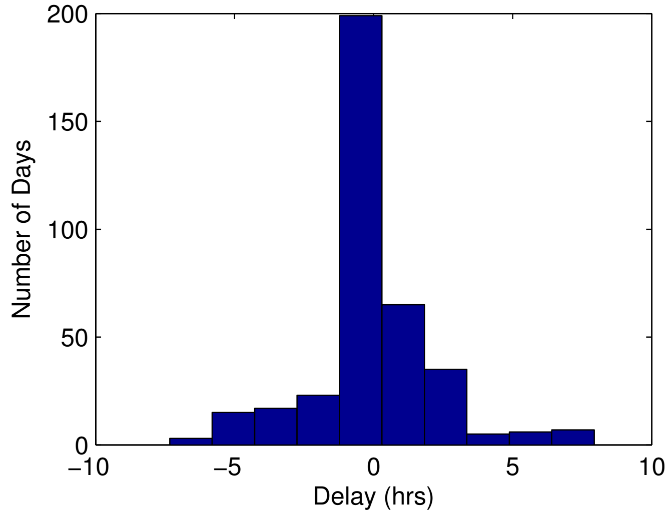

Figure 2.2: Number of days with different density delays using the NRLMSISE-00 model.

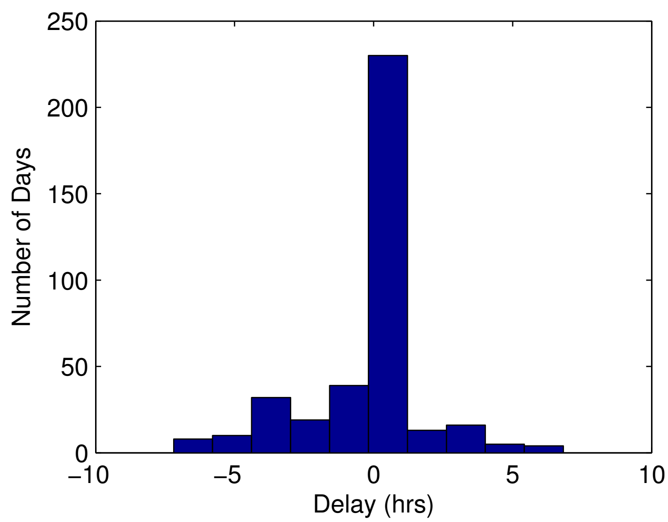

Figure 2.3: Number of days with different density delays using the JB2008 model.

The actual and smoothed densities in Figure 2.1 show the differences that can be expected between the measured and modeled densities. Over this time period, the model tends to over-predict the density. The primary focus of this research though is the time delay, so the over-prediction of the density will not be discussed. When examining the actual densities, it can be difficult to determine the peak densities and subsequent time delay. In the smoothed densities though, clear peaks can be seen and a delay in those peaks is obvious. Figure 2.2 contains a histogram of the

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number of different delay times that were seen in the data, using the NRLMSISE-00 model. This figure shows that not only does a delay in the prediction of density sometimes occur, but the model also sometimes predicts a premature increase in the density. These early increases are indicated by the negative delays. In this histogram, negative values indicate a delay in density prediction while positive values indicate a premature increase. The majority of the delays and early increases are approximately 5 hours, with most being under 3 hours. The time difference sometimes reaches 6 hours, but these cases are much less frequent. From this information, it was decided to focus the study on delays and early increases of 1 to 6 hours. Also, for comparison, in Figure 2.3, a histogram of the delays using the JB2008 model is shown. The plots show a similar trend in the delays seen, and neither model appears to have drastically better performance.

It should also be noted that the largest time differences do not always occur at the largest Kp values. In fact, the storm shown in Figure 2.1 was the largest storm in the study, but the delay at this time was approximately 1.5 hours. This implies that the magnitude of the storm is not the only factor in the creating these time delays.

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Chapter 3

Short-Term Time Delays Using an Analytical Density Model

Before examining the errors arising from using empirical density models, some insight into orbit errors may be gleaned from examining the effects of time delays on an empirical atmosphere model. By using a simple analytical model, characteristics of the density perturbations such as its amplitude can be specified, and then the effects of time delays may be isolated. Previously, Anderson et al. showed that the primary consideration in modeling a density function was the imparted impulse and that functions of different shapes with the same impulse resulted in similar orbit changes. Thus, half of a sine wave over half of an orbit will be used here to model an increase in density. To accomplish this, two spacecraft are integrated forward using the same initial conditions. The first encounters the specified perturbation, and is integrated over 24 hours. The second encounters that same perturbation, but at a different time. Figure **??** illustrates this example.

Different cases were computed while varying the time delay up to four hours. The amplitude of the variation was also changed up to 200 percent of the nominal density at the specified altitude, which for these simple cases was computed using the 1976 standard atmosphere.[16] The results are plotted in Figure 3.1 for altitudes of 400 km and 700 km. The effects at an altitude of 400 km sometimes approach over 20 m, which could be noticeable for some applications, while the effects at 700 km are relatively minor. Keep in mind that these effects would scale with area or the ballistic coefficient, so even these small errors may become of significance relative to the U.S. Air Force requirements if the area of the spacecraft were to become much larger.

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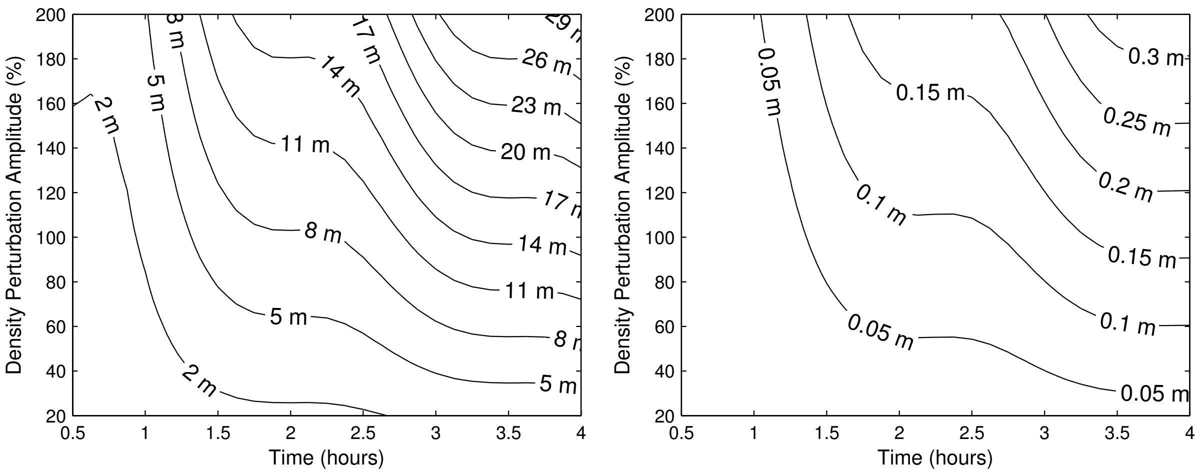

(a) 400 km (b) 700 km

Figure 3.1: Final positions differences after a 24 hour integration for different combinations of time delays and density perturbation amplitudes. In each case, the perturbation is modeled so that it covered half of a revolution.

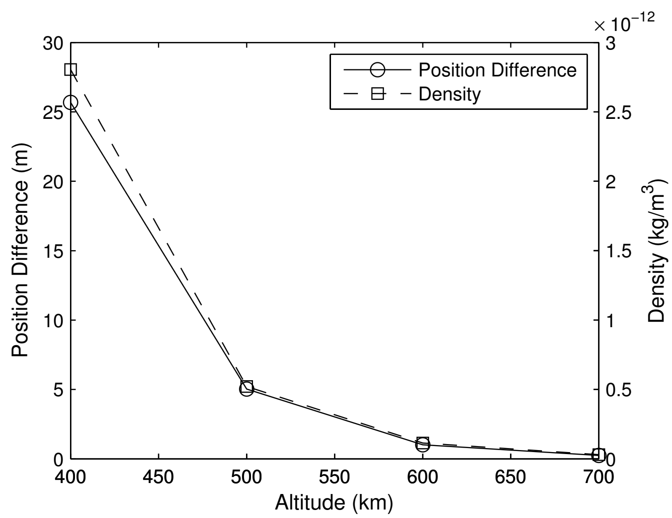

Figure 3.2: Position differences after a 24 hour integration at various altitudes for a time delay of three hours and a density perturbation amplitude of 200 percent.

The effect of varying the altitude on these results may be further examined by computing the position differences for a specific case over several altitudes. This process was done for a specific case with a time delay of three hours and a density perturbation amplitude of 200 percent in Figure 3.2. The position differences decrease dramatically at 500 km to approximately 5 m and further

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down to approximately 1 m at 600 km. Plotting the results compared to the density reveals that they closely follow the value of the density at the specified altitude as would be expected.

The orbit errors are small here compared to what will be seen in later sections. This is due to the fact that an analytical model is used here, and does not have the same variability as real world densities. The most important conclusion to draw from this analytical model study is that the errors increase with lower altitude. This indicates that while a certain delay may not cause relevant errors at a higher altitude, that same delay may have much more drastic effects at a lower altitude.

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Chapter 4

Orbit prediction Using Density Models with no Delays

Before examining the effects of time delays in density models on orbit prediction, it is necessary to examine the total error that arises from using density models to represent the actual atmosphere so as to determine the importance of the time-delay errors relative to the orbit errors. This was briefly examined for the years 2003 and 2007 in Anderson et al., where the errors arising from using NRLMSISE-00 densities in place of CHAMP densities was examined. This problem is again examined here in more detail, using updated CHAMP densities as well as comparing densities obtained from the JB2008 model. The errors are examined for the years 2003 through 2008.

In Figure 4.1, the difference between the CHAMP and NRLMSISE-00 model densities are shown. The model densities are computed at the CHAMP satellite's height. The difference largely fluctuates around 0. The largest difference between the two densities occurs in 2003 during the large storm in late October. The model densities tend to deviate more in the later years, but it is unclear as to why this deviation occurs.

Figure 4.2 contains a similar plot, this time using the JB2008 model to compute the model densities. As with the NRLMSISE-00 model, the differences between the CHAMP densities and JB2008 densities typically stay around 0. In contrast to the NRLMSISE-00 model though, the largest deviation does not occur during the October 2003 storm. While there is still a large deviation during this time, the largest occurs in 2005. That year still saw some large Kp values and geomagnetic activity, but was on the whole much less active than 2003. There is also a similarly large deviation in 2008, which was the least active year of all those which were studied. This may

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indicate that high magnetic activity is not the only cause of these large density differences in the model.

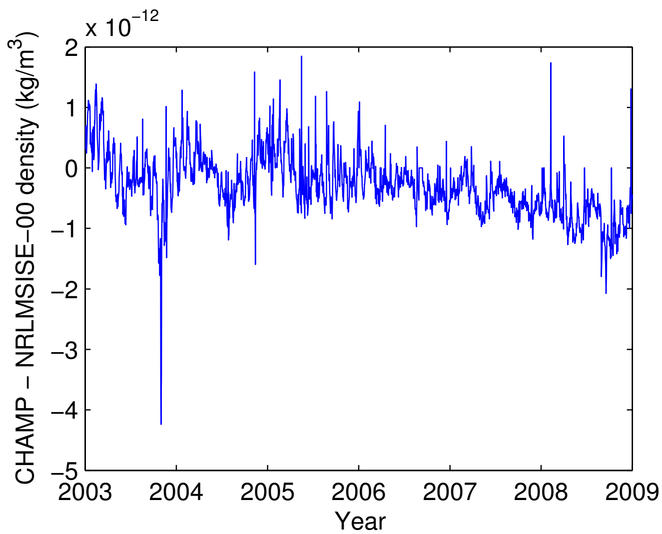

Figure 4.1: Difference between mean densities computed using NRLMSISE-00 model for each day at the CHAMP satellite's altitude.

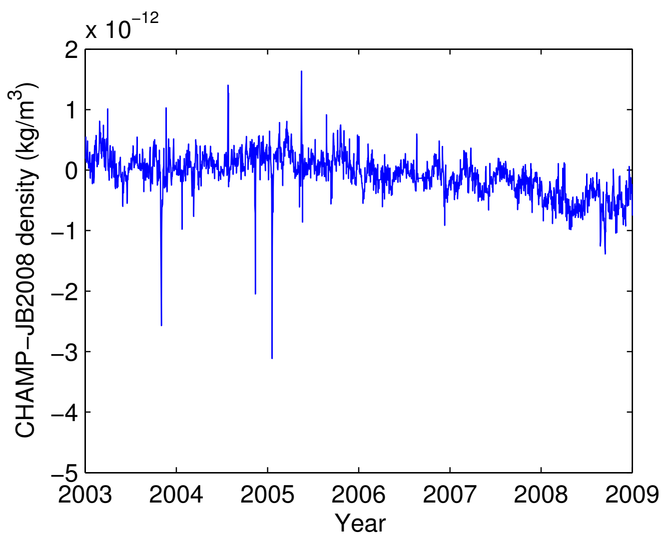

Figure 4.2: Difference between mean densities computed using the JB2008 model for each day at the CHAMP satellite's altitude.

It is straightforward then to compute the effects of the density models on orbit prediction. A simulation was performed to compare the effects of using the model densities and CHAMP

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densities in orbit propagation. In the simulation, a spacecraft with a mass of 500 kg, and a polar circular orbit with an altitude of 400 km was assumed. The equations of motion used are those described earlier, and include the effects of J2 as well as drag. The coefficient of drag assumed was 2. This spacecraft was integrated over 24 hour intervals for the years 2003 through 2008. In order to compare the effect the different densities have on the satellite's orbit, the simulation is performed twice. The first simulation uses the CHAMP densities normalized to 400 km. These densities are smoothed in order to remove the orbital effects as described earlier. The second simulation is performed with densities provided by the NRLMSISE-00 model at 400 km, which are also smoothed. In computing the model densities, the best model inputs are assumed, meaning that the values for the ap planetary index and F10.7 daily solar flux are the exact values seen on that day and not estimates.

The differences in the orbit are computed in the radial, in-track, and cross-track directions. The maximum difference from each day is then taken and these differences are plotted in Figure 4.3. The results agree with what was previously seen by Anderson et al. for the years 2003 and 2007, where 2003 was a more active year and thus has larger orbit errors, while 2007 was much less active and has smaller orbit errors.

Table 4.1: RMS of orbit differences using NRLMSISE-00 and JB2008 models.

Model	Radial (m)	In-track (m)	Cross-track (m)
NRLMSISE-00	10.511	748.771	0.162
JB2008	5.763	407.115	0.089

The direction in which the largest errors occur is in-track, as drag opposes the velocity and thus mainly affects the satellite's orbit in this direction. The radial direction is coupled with in-track, and as such also contains orbit differences that are relevant at times. During the October 2003 storm, the radial error reaches over 120 m, which is the maximum difference it reaches. This error is greater than the magnitude of concern to the Air Force for a satellite with a 400 km orbit. For conjunction analysis, a difference of over 100 m is also relevant. In this direction though, an error over 100 km only occurs during a large storm time. For other times, the error remains below

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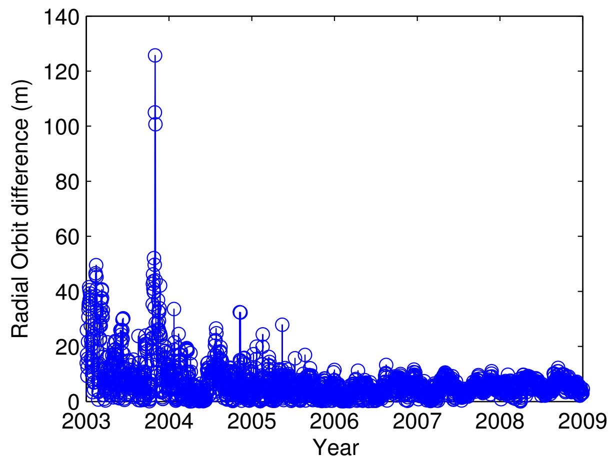
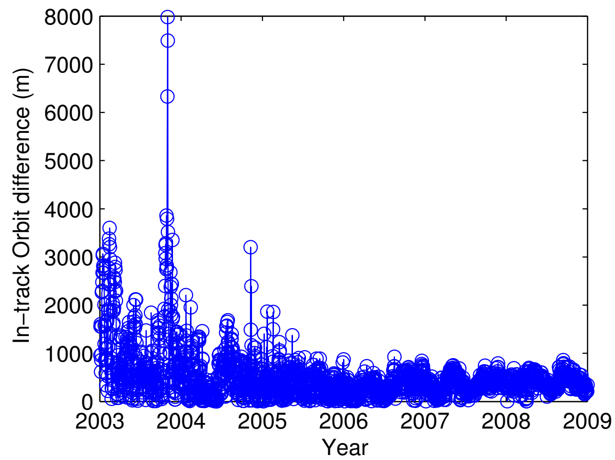
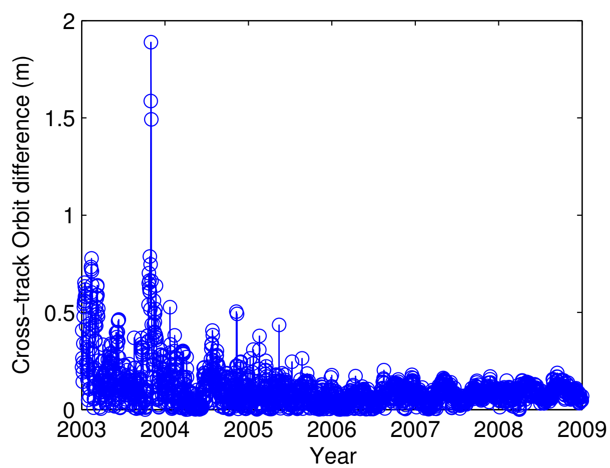


(a) Radial



(b) In-Track



(c) Cross-Track

Figure 4.3: Spacecraft orbit differences computed using CHAMP density values and NRLMSISE-00 model density values. The orbit errors are computed after a 24 hour integration.

60 m and never increases over 20 m after the latter part of 2005. Thus, the radial errors do not typically have an appreciable effect on orbit prediction, especially when compared to the differences in the in-track direction. It should also be noted that the errors increase as the altitude decreases, so this may also become more relevant at lower altitudes.

The in-track orbit errors are much larger, with much of the active years seeing errors of greater than 1 km. During the early part of 2003, the errors are consistently greater than 1 km, reaching nearly 4 km several times. During the October 2003 storm, the orbit error reaches 8 km.

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Errors as high as 2 km can be seen until the end of 2005, as the geomagnetic activity begins to wane and the solar minimum is more in effect. During the latter and less active years of the study, the orbit errors stay below 1 km. Even during the less active years, the orbit errors are much greater than the 100 m orbit error of significance to the Air Force. These errors are also of great significance for conjunction analysis, as miss distances are typically calculated at several hundreds of meters. The RMS calculated from these errors, shown in Table 4.1 is nearly 750 m, so even the average error is of significance. The cross-track direction, which is consistently under 2 m, is not relevant when compared to the other directions and is not discussed here.

The same simulation was performed again, instead using the JB2008 model in order to compute the model densities. The orbit errors from the simulation are presented in Figure 4.4. The results from this simulation are similar to the errors seen with the MSISE model, but a few differences exist.

On average, the orbit errors using the JB2008 density model are smaller than those seen when using the NRLMSISE-00 model, but the errors are still relevant. In the radial direction, the maximum error that is reached is almost 80 m, and that is found during the October 2003 storm. This error falls below the errors of interest for the Air Force, and is likely not relevant to conjunction analysis. Something that can be seen when examining the radial direction is that the errors in later, less active years can sometimes still be quite large. In 2005, the error in the radial direction reaches nearly 70 m, almost as large as what was seen in October of 2003. This will be more relevant when examining the in-track errors.

The maximum error seen in the in-track direction for the JB2008 model comparison is approximately 6 km. This occurs during the October 2003 storm, as expected from the previous results. In general, the errors tend to stay below 2 km, even for the earlier, more active years. A notable exception though is 2005, where the orbit error reaches nearly 5 km. This was also seen in the radial direction, but it is more important here as the error is much larger and of more significance. That year shows the largest errors after 2003, despite being on the tail end of the active years. Despite this, 2005 had more days with high Kp values overall than 2004, which may

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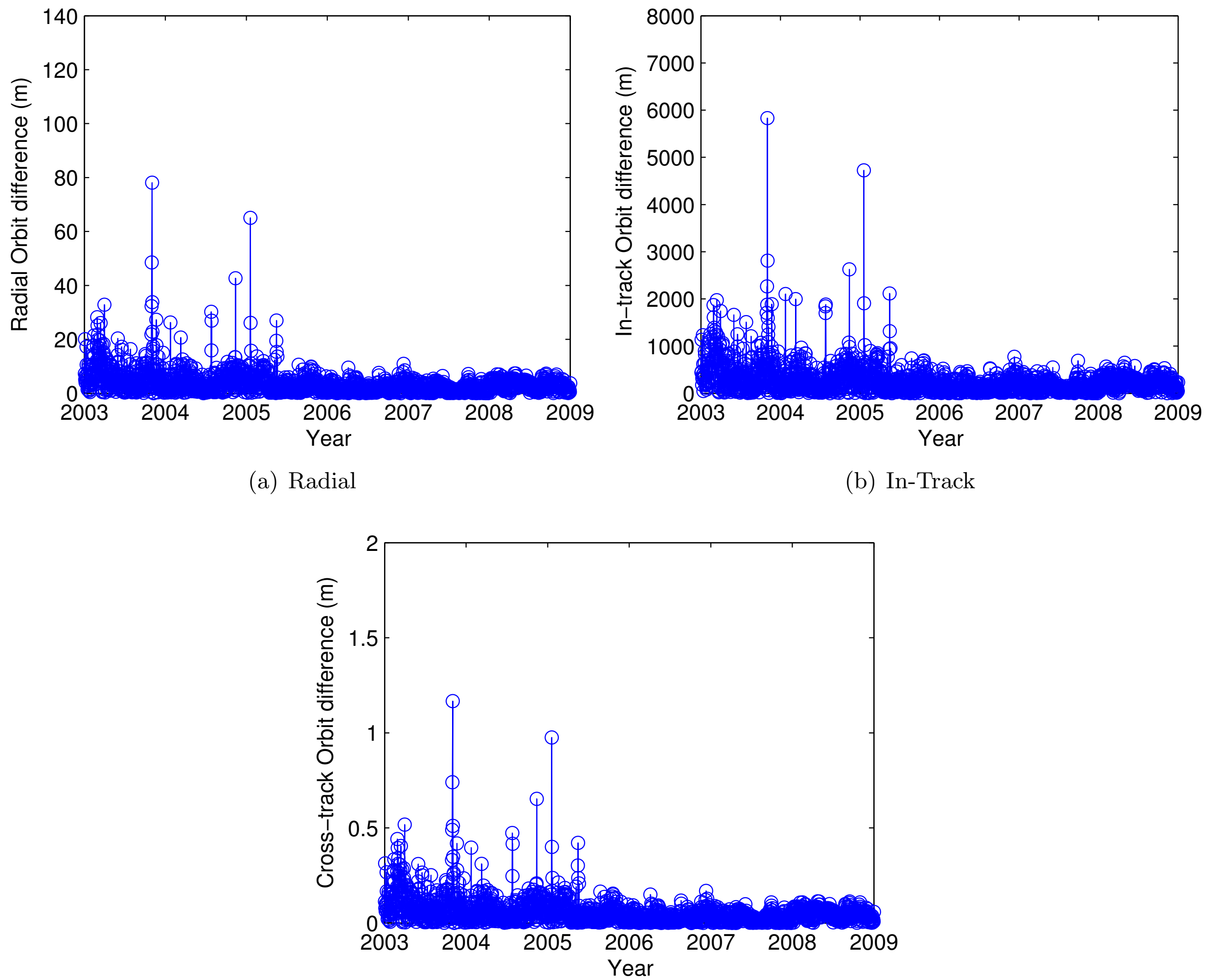

(a) Radial

(b) In-Track

(c) Cross-Track

Figure 4.4: Spacecraft orbit differences computed using CHAMP density values and JB2008 model density values. The orbit errors are computed after a 24 hour integration.

explain the higher errors. This large error is also not as prominent in the MSISE model, where the errors in 2005 are no greater than those seen in 2003.

Despite smaller errors on average, the errors that arise from using the JB2008 model are still of significance for satellite operators. The largest error that occurs reaches nearly 6 km, and the errors during active years are typically over 1 km. As the geomagnetic activity lessens, the errors drop below 1 km, but the RMS computed from the data, also shown in Table 4.1 is 407 m. This is greater than the relevant errors to the Air Force, and is also important for conjunction analysis.

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Again, the cross-track errors are below 2 m, and are not reported here.

The JB2008 model performs slightly better than the NRLMSISE-00 model, with smaller maximum errors and smaller errors on average. It did, however, show a large error at a time when the NRLMSISE-00 did not, indicating that the JB2008 model may be affected by more than just the magnitude of the geomagnetic activity. Both models exhibited the same behavior as well, in that the more geomagnetically active years, 2003 through 2005, showed larger errors on average, while the subsequent and less active years never had errors over 1 km.

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Chapter 5

Delays In Empirical Models

While using exact model inputs is obviously the preferred method for post processing, as orbit prediction results are being generated some delay is often introduced into the model inputs. In the section on modeling densities without delays, the best known input parameters were used in order to compute the model densities. In the study presented in this section, time delays are introduced into the density input parameters for the NRLMSISE-00 and JB2008 models. The effects of these time delays on orbit prediction are then examined.

Examining the effects of time delays in the models on orbit prediction allows one to get an understanding of the current capabilities of the models. It was already shown previously how predicted orbits computed with density models compare to those computed using real world densities. Now, the effects of time delays in the models are examined to best understand the amount of error that can result from them. The simulation is performed for the years 2003 through 2008, to cover both an active year and then quieter years. Using delayed real world inputs allows for actual geomagnetic fluctuations to be examined, and is more insightful than providing simulated geomagnetic indices.

To get an idea of the differences in density that adding a delay to a model can cause, the density profiles for 1 day in 2003, computed using the NRLMSISE-00 model, are presented in Figure 5.1(a). Here, the nominal density profile is shown along with a density profile delayed by 3 hours, as well as an advance density profile of 3 hours. From examining this figure, the differences in the density profiles are evident, but they do not appear to be very large. To illustrate the effects

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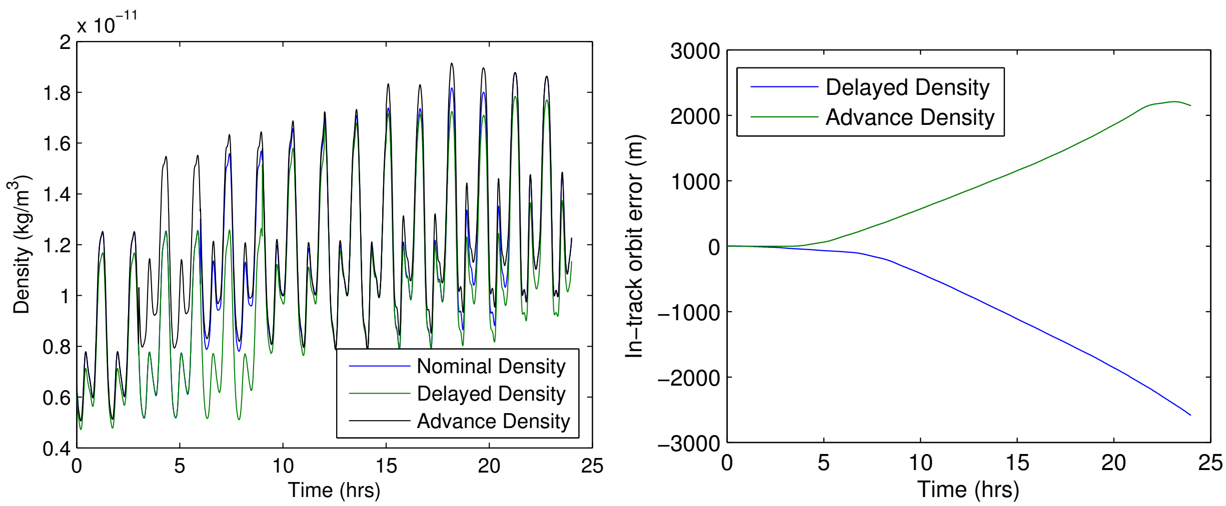
of these time offsets in the densities on orbital prediction, a satellite is integrated over the course of this day. The truth case is taken to be a model with exact inputs, which in this case is the NRLMSISE-00. Then another satellite is integrated using the offset density, and the difference between the two orbits is presented. Figure 5.1(b) shows the in-track error over the course of 1 day for the 3 hour time shifts in both directions. It can be seen that despite the seemingly small density differences seen in Figure 5.1(a), the orbit error still grows to be quite large by the end of a 24 hour integration.



(a) Density Profile (b) Orbit Differences

Figure 5.1: Delayed, advanced and nominal density profiles and resulting orbit differences for October 29, 2003

5.1 NRLMSISE-00 Model Delays

This simulation was performed for each day over the years 2003 through 2008. The time shifts introduced into the model inputs range from 1 to 6 hours in both directions. The satellite used in the integration is similar to what was used in the previous model comparison without delays. After performing the integration over 24 hours, the maximum errors in the radial, in-track, and cross-track directions are then reported.

The results from the 3 hour delay simulation using the NRLMSISE-00 model are shown in

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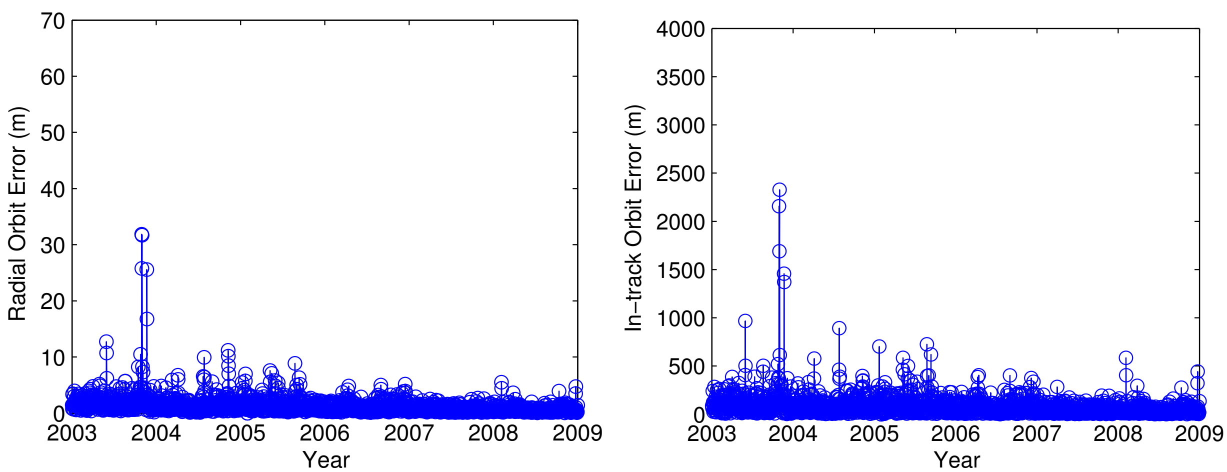
Figure 5.2. The radial and in-track errors are shown. As seen in the previous section, the cross-track errors are very small and not significant, and so are not shown here. The radial errors are also small compared to the in-track errors. They only once increase over 30 m, and typically stay below 10 m, making them of little to no concern to the Air Force or those doing conjunction assessments. It will be shown though that they do increase with larger time offsets, and as such may be more relevant with a larger delay.

The in-track error is much more significant. The error reaches nearly 2500 m, which is well above the relevant errors for the Air Force. A kilometer is also a significant miss distance for conjunction assessment, and an error of greater than 1 km could cause serious problems. An error this large is only seen once though, and that is during the large storm of October 2003, which was the largest storm seen in this study. Large excursions such as this are not seen frequently, even for the rather active year of 2003. In 2003, the error only rises above 1 km once, and in 2004 it is always under 1 km. As the study moves to the quieter years, the errors are typically below 500 m. It should be noted that the error will increase with a lower altitude, so delays that don't cause appreciable orbit errors at this altitude may be more relevant at lower altitudes.



(a) 3-Hour Delay Radial

(b) 3-Hour Delay In-track

Figure 5.2: Maximum orbit errors for each day for a 3-hour delay using NRLMSISE-00 model.

Also studied was the case where the satellite encountered a density that was increased 3 hours

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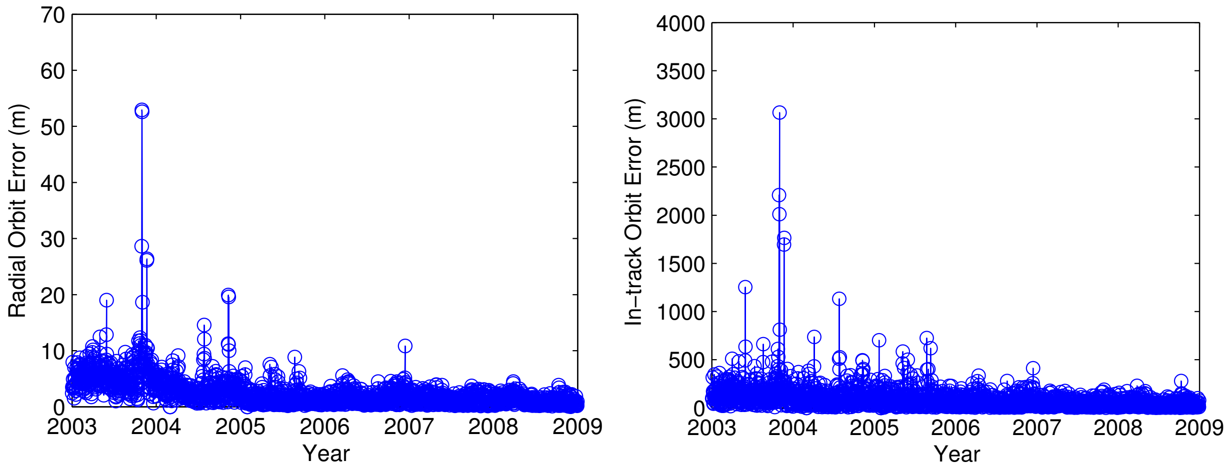
early instead of delayed. The results of this case are presented in Figure 5.3. The errors seen here are not drastically different from the delayed case. Again, the radial errors are on the order of tens of meters, and as such are not significant compared to the in-track errors. The maximum in-track error for this case reaches slightly over 3000 km. This is more than 500 m larger than the delay case. As the error is already quite large and relevant for most cases, this error only increases the problem.



(a) 3-Hour Advance Radial

(b) 3-Hour Advance In-track

Figure 5.3: Maximum orbit errors for each day for a 3-hour advance using NRLMSISE-00 model.

It is also interesting to look at a time shift of 6 hours as a worst case. Delays of this magnitude to not typically occur, but are present and may be more common during solar maximum. First discussed is the 6 hour delay case, which is shown in Figure 5.4. Again, the radial error is does not reach the magnitudes that are relevant to the Air Force, and so is not appreciable compared to the in-track errors.

The in-track error though is much larger than what was seen for the 3 hour case. It reaches over 4000 m, which is nearly 2 times the largest error seen in the 3 hour delay case. An error this large only occurs once in 2003, but is obviously very significant. There are also several times that the error increases to well over 1000 m throughout 2003 and 2004, nearing almost 2000 m. These errors are of obvious significance for the Air Force and for conjunction assessment, as errors of 2000

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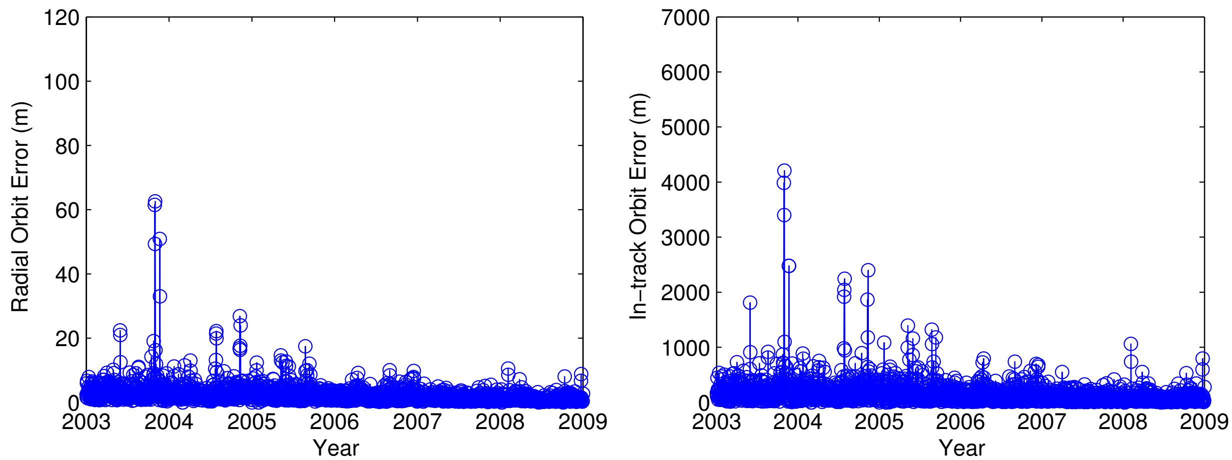
m are twice the size of the watch volume. During quieter years, the errors typically remain below 1000 m, but occasionally reach 1 km in magnitude, making them relevant in quiet times as well.



(a) 6-Hour Delay Radial

(b) 6-Hour Delay In-track

Figure 5.4: Maximum orbit errors for each day for a 6-hour delay using NRLMSISE-00 model.

From examining the 3 and 6 hour delay plots, it can be seen that the orbit errors follow the same behavior for each delay magnitude, and only the magnitude of the errors changes between them. Thus, it is best to get an idea of the average behavior of the errors over the timespan. Thus, the RMS of the maximum errors was computed for each delay, and can be seen in Table 5.1. The RMS of the errors are of a significant magnitude to the Air Force for delays over 1 hour. At larger delays, such as 5 and 6 hours, the errors may be cause for concern when performing conjunction assessments, depending on the variability of the density at that time.

Table 5.1: RMS of maximum orbit differences for NRLMSISE-00 model density delays.

Delay (h)	Radial (m)	In-track (m)
1	0.9844	53.2288
2	1.6727	100.2899
3	2.1451	143.7125
4	3.0912	202.3635
5	3.7124	248.3190
6	4.2082	290.3454

For comparison, the 6 hour advance density case is also shown in Figure 5.5. The errors are

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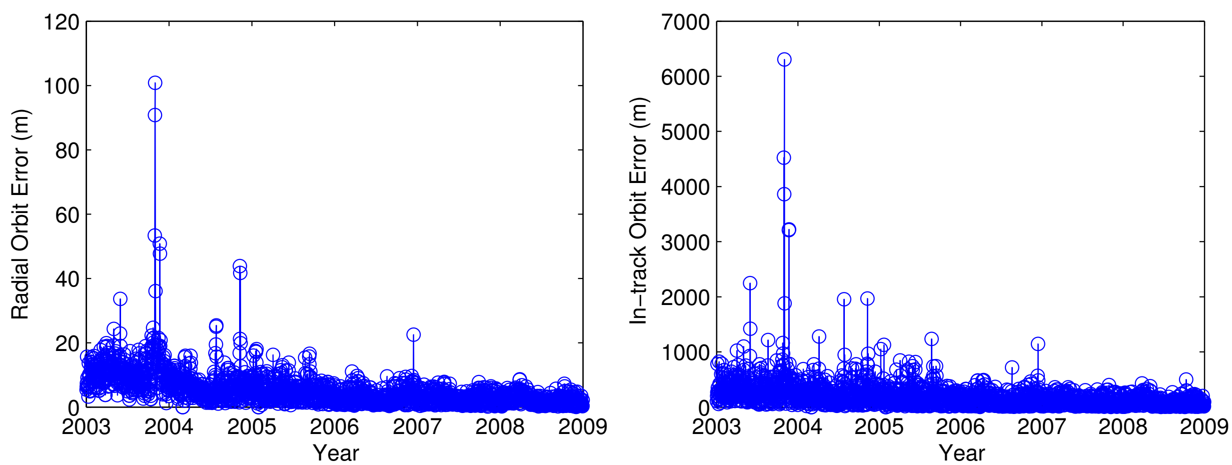
again similar to the delayed case, with magnitude of the errors being larger over all. The max error in the radial case does reach over 100 m, which is an error of interest to the Air Force for this altitude. It is only significant though, if errors in the radial direction are relevant as opposed to simply total position error, since the in-track error dominates the total position error.

The maximum in-track position error is 6000 m, nearly 2000 m larger than what was seen in the delay case, and nearly 2 times the 3 hour case. Besides the maximum case, there are several times where the error reaches 1000 m or greater over the two years. The 6 hour advance case leads to the worst errors for the NRLMSISE-00 model.



(a) 6-Hour Advance Radial

(b) 6-Hour Advance In-track

Figure 5.5: Maximum orbit errors for each day for a 6-hour advance using NRLMSISE-00 model.

It is also desirable to examine the overall errors for the advance cases. The RMS of the errors for each of the advance cases is shown in Table 5.2. The errors here are again larger than the delayed cases, with the 6 hour advance case being almost 100 m larger than the delayed case. Once again, the errors are significant for the Air Force for early increases of 2 or more hours.

Predicting early or late densities in the NRLMSISE-00 model is shown to cause orbit errors of significant value for all but the smallest delays. The small delays also still report maximum errors of significance during times of large geomagnetic activity. It should be noted though, that the small delays are more likely to occur when the geomagnetic activity is not large, and the opposite will

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Table 5.2: RMS of maximum orbit differences for NRLMSISE-00 model density early increases.

Delay (h)	Radial (m)	In-track (m)
1	1.4058	49.4876
2	2.4481	105.0309
3	3.7797	166.7233
4	5.0581	214.8104
5	6.0843	272.0271
6	7.5327	335.7388

occur with larger delays when the activity is high.

5.2 JB2008 Model Delays

The study described in the previous section was also performed for the JB2008 density model. Here, densities computed using the JB2008 model with exact inputs was used as the truth density. A second satellite was again integrated using time shifted densities in either direction, and the maximum errors after a 24 hour integration were reported. The simulation was again performed over the years 2003 through 2008.

The results of the 3 hour delay case are presented in Figure 5.6. The first thing that should be noted is that the errors are larger in general than the errors from the NRLMSISE-00 model study. The maximum radial error is nearly twice the radial error seen with the NRLMSISE-00 densities, but is still not relevant compared to the in-track errors.

The in-track error reaches to over 3500 m for its maximum case. This is over 1000 m larger than what was seen for the other model, and occurs at the same time (late October 2003). There are also several days around this maximum time where there errors are over 2000 m. The orbit errors stay well above significant errors for the years studied, reaching nearly 1000 m on several occasions throughout 2003 and 2004. As with the NRLMSISE-00 model, the errors mainly stay below 500 m during quieter times, but there are much higher errors during more active times.

The early density increase is also studied for the JB2008 model. The results of the 3 hour case can be seen in Figure 5.7. These results do not differ greatly from the delayed density case.

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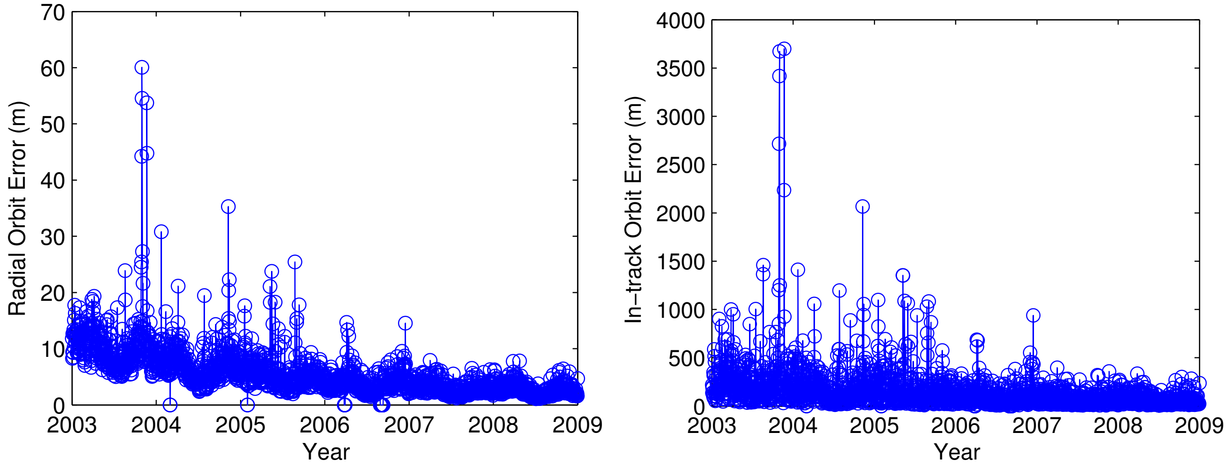

(a) 3-Hour Delay Radial

(b) 3-Hour Delay In-track

Figure 5.6: Maximum orbit errors for each day for a 3-hour delay using JB2008 model.

The peak density is slightly larger, but on average the densities do not differ much from each other. Tables 5.3 and 5.4 contain the RMS for each time shift in the advance and delay cases. These indicate no large difference between the overall performance of the JB2008 model when faced with early or late density shifts. The RMS of the errors is large for each time shift. Even for a 1 hour delay or advance, the RMS is over the Air Force errors of interest for the satellite height. At 6 hours, the error is nearly 500 m, which is significant for conjunction analysis. An error of 500 m is half the size of the Watch Volume used by GSFC safety volume for conjunction analysis.

Table 5.3: RMS of maximum orbit differences for JB2008 model density delays.

Delay (h)	Radial (m)	In-track (m)
1	2.8499	112.0291
2	5.0934	195.6135
3	7.0124	271.5894
4	8.7646	356.6057
5	10.2013	438.2856
6	11.0077	488.0378

The 6 hour cases are also shown here for the JB2008 model to compare with the NRLMSISE-00 model. As expected from the 3 hour case and the RMS of the 6 hour shifts, the JB2008 model performs worse than the NRLMSISE-00 for this case as well. The radial and in-track errors are

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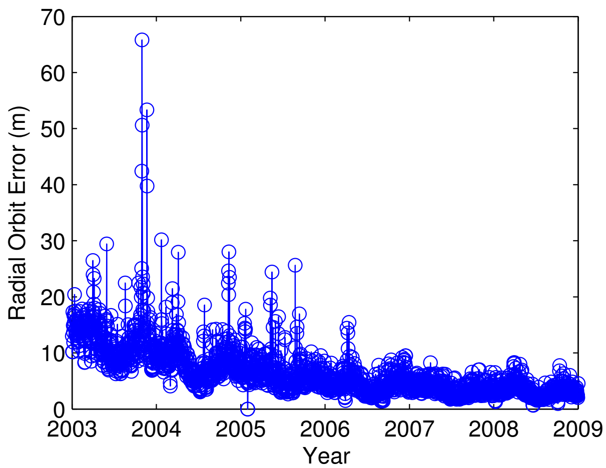
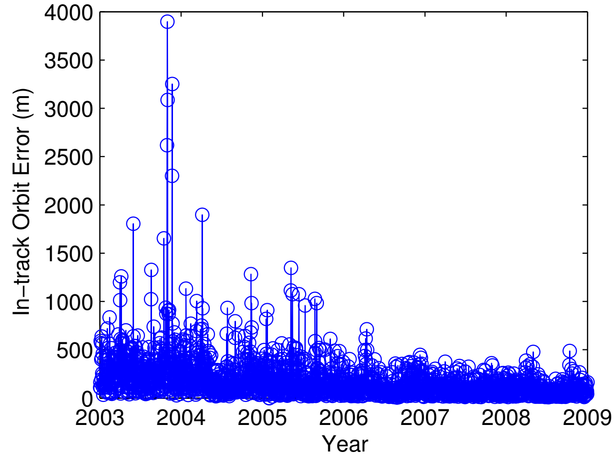


(a) 3-Hour Advance Radial



(b) 3-Hour Advance In-track

Figure 5.7: Maximum orbit errors for each day for a 3-hour advance using JB2008 model.

Table 5.4: RMS of maximum orbit differences for JB2008 model density early increases.

Delay (h)	Radial (m)	In-track (m)
1	2.7324	93.6017
2	5.4066	189.6168
3	8.0884	286.5528
4	10.5100	369.2577
5	12.6425	441.4058
6	14.5700	511.2572

presented for the 6 hour delay case in Figure 5.8. The maximum errors are well above errors of concern. During October of 2003 the error reaches nearly 7000 m. There are also several times where it is over 2000 m. The radial error does not reach errors of concern, but is still very small compared to the in-track error.

The 6 hour advance density case is shown in Figure 5.9. The performance is again similar to the delay case. In this case, the maximum densities that are seen are slightly less than what was seen for the delay case. Despite this, from examining Tables 5.4 and 5.3, it can be seen that the advance density errors are on average greater than the delayed density. This was also the case with the NRLMSISE-00 model. Neither of the models have significant differences in performance for early or late density increases, as the RMS of the errors are only tens of meters apart.

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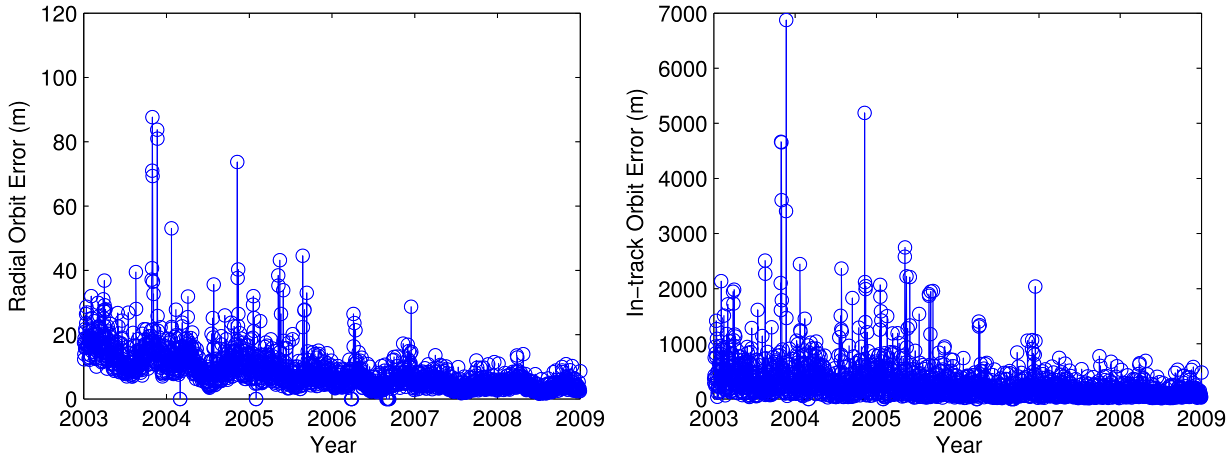
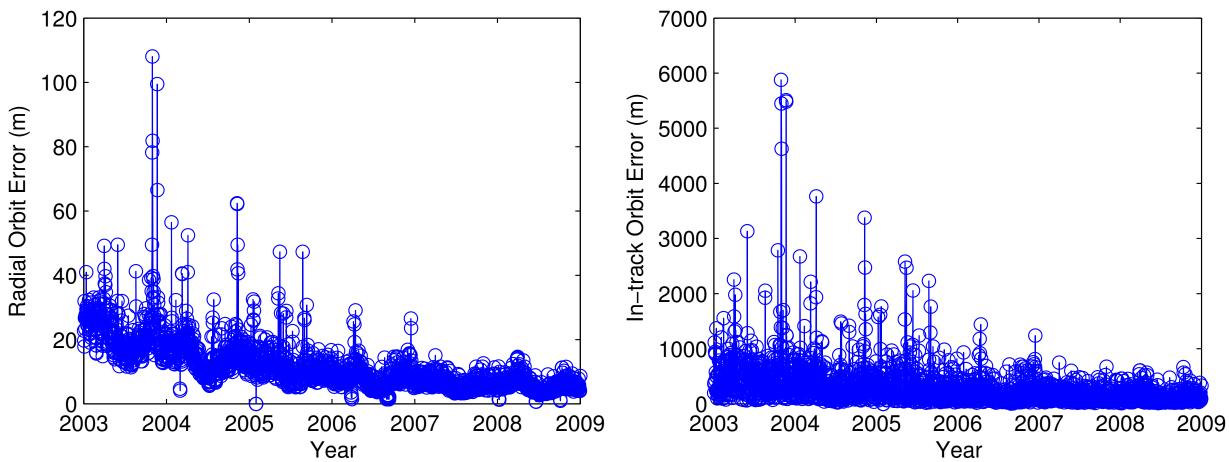


(a) 6-Hour Delay Radial
(b) 6-Hour Delay In-track

Figure 5.8: Maximum orbit errors for each day for a 6-hour delay using JB2008 model.



(a) 6-Hour Advance Radial
(b) 6-Hour Advance In-track

Figure 5.9: Maximum orbit errors for each day for a 6-hour advance using JB2008 model.

The results from introducing a time shift into the model densities indicate that these time shifts have a greater effect on the JB2008 model. The orbit errors from the time shifted densities in that model were significantly larger than those seen in the NRLMSISE-00 model. The JB2008 model uses hourly indices when it computes density during times of high geomagnetic activity. This means that delays of an hour or larger could have a significant effect on the density computed, as the activity in from the a different hour may be significantly different. Contrast this with the

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NRLMSISE-00 model, where the indices used are reported every 3 hours. Thus, smaller time shifts may not even cause a different density to be reported as the time resolution is small and a different index may not even be used. Even for the large delays, the ap index used may not differ that greatly from one reporting time to the next.

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Chapter 6

Orbit Prediction Errors with Delays in Smoothed CHAMP Density Data

In previous sections, the effects of density delays on analytical density models were examined, as well as the effect of time delays on empirical density models. This allowed for the examination of the capabilities of the two density models to be examined when faced with density delays. It is now desirable to examine the effects of a density time delay on orbit prediction using real-world density fluctuations as opposed to empirical density models.

The reason for this simulation is to understand what effects time delays alone have on orbit prediction. This assumes that densities could be predicted exactly on most occasions, but time delays may still exist due to geomagnetic storms and cause an error in density prediction. It was seen previously that during less geomagnetically active years, the orbit errors arising due to using an empirical model were small during less active times, where density delays are not as likely to occur. Assuming that density could be predicted nearly perfectly for quiet times is thus not an unreasonable assumption.

The densities used in this analysis are the CHAMP densities mapped to 400 km. Again, the densities are smoothed in order to remove variations in the density which are related to the location of the spacecraft as it travels through its orbit. This smoothing process removes short term density variations while still retaining the density variations arising from geomagnetic storms.

A similar process to the previous simulations is used here. A spacecraft is integrated in a 400 km polar orbit with the same spacecraft properties used previously. The first spacecraft is integrated using the smoothed density profile at 400 km for a given day. This density is defined as

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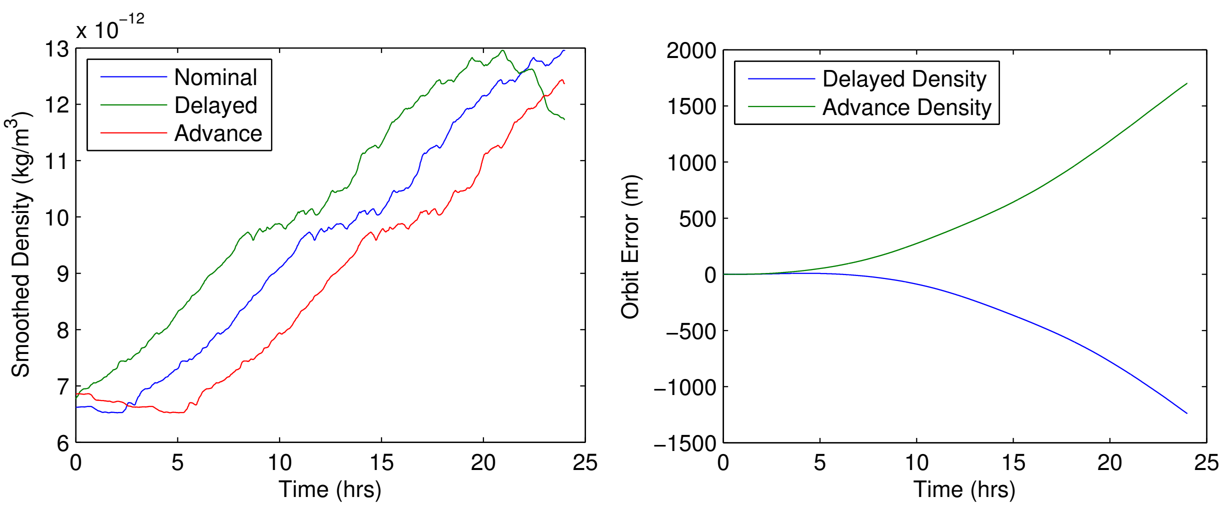
the truth density for this study. A second, identical spacecraft is integrated with the same initial conditions, but this time using a density profile that is shifted a number of hours either forward or backwards in time. Thus, where the nominal satellite would encounter a density at time t, the delayed satellite would encounter the same density at time t-3. An example of the smoothed densities over one day can be seen in Figure 6.1(a). The nominal density profile is shown along with the 3 hour delayed and 3 hour advance cases, as typical examples since 3 hour delays are common throughout the data. In Figure 6.1(b), the difference between the position of the satellite which encountered the nominal density and the satellite which encountered the offset density are shown. AT the epoch time in this plot, the spacecraft has been under the influence of a time-shifted density for 3 hours for the delayed density case. For the advanced density case, it enters the influence of the CHAMP density 3 hours before it occurred for the nominal spacecraft. A premature increase in density results in larger orbit errors than a late increase in density, but both errors are of the same magnitude.



(a) Density Profile (b) Orbit Differences

Figure 6.1: Delayed, advanced and nominal density profiles and resulting orbit differences for October 29, 2003

This study is then performed for the years 2003 through 2008. The integrations are performed over 24 hours for each day, and the maximum difference at the end of each day is recorded. Figure

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6.2 contains the errors in the radial and in-track direction for a delay of 3 hours. Again, the 3 hour delays are included since a delay of 3 hours is typical. Figure 6.3 contains the errors in the radial and in-track direction for a 6 hour delay to illustrate the maximum delay. Six hour delays were not common in the data but are presented to illustrate a worst-case scenario. The errors for increasing delays have the same profiles, but contain larger or smaller magnitudes for longer or shorter delays. Thus, only these two cases are shown here. The cross-track case is not shown because the errors are all at the sub-meter level and thus are not relevant here.

Examining the figures, it can be seen that the errors in the radial direction are not significant by Air Force standards or for conjunction analysis. Even with the 6 hour delay, the radial error only reaches a maximum of 60 m. It otherwise stays below 20 m for 6 hours, and only reaches a maximum of slightly over 30 m for a 3 hour delay. As shown in the previous solutions, the largest errors again occurred in the in-track direction. The largest errors again occur during the October 2003 storm, with the errors in the 3 hour delay case reaching 3 km, and over 5 km for the 6 hour case. Other than this large error though, most of the errors are below 1 km. For the 3 hour case, the errors typically fall below 500 m, even for the active year of 2003. Other than the October storm, the error only reaches 1 km two other times, once in late 2004 and another time in 2005. These errors scale up for the 6 hour case, but even for the large delays the errors fall off to less than 500 m for the less active years. The errors for all of the years can be summarized in Table 6.1, which contains the RMS values for each delay in the three directions.

From this table, it can be seen that the delays do not cause average errors of relevancy for 1 or 2 hours. At 3 hours, the RMS is 138 m, and increases for longer delays. This is above the relevant error for the Air Force at satellites' with a height of 400 km. Though not plotted here, the maximum error for a 1 hour delay does reach 1 km, for the large storm in 2003, which is a relevant error for the Air Force and conjunction analysis. These errors though only occur for highly active times. For less active times, the errors are very small and only are occasionally relevant. Also, for less active times, a shorter delay would be expected, so the 1 hour delay is more applicable to the less active years while the 6 hour delay is more relevant to the earlier, more active years.

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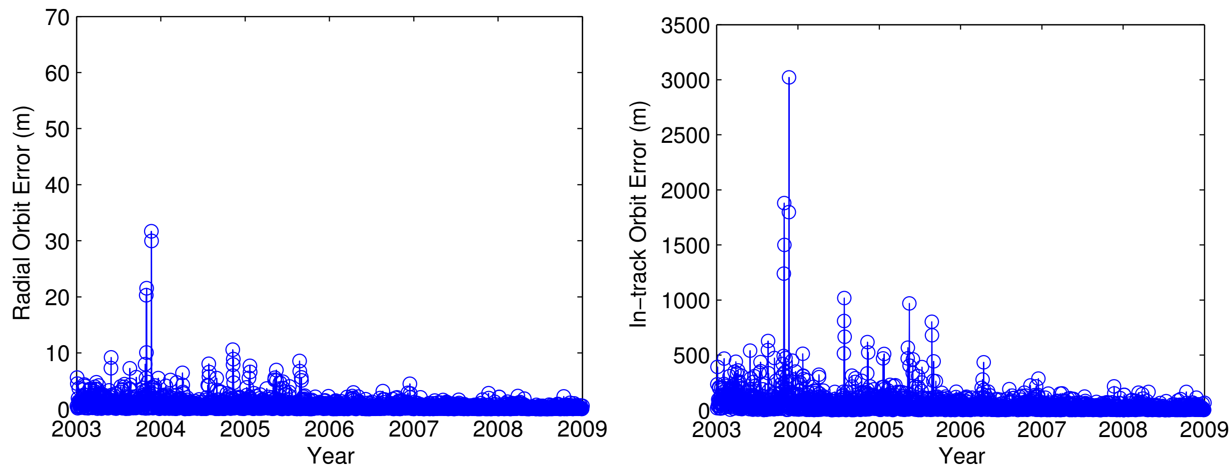
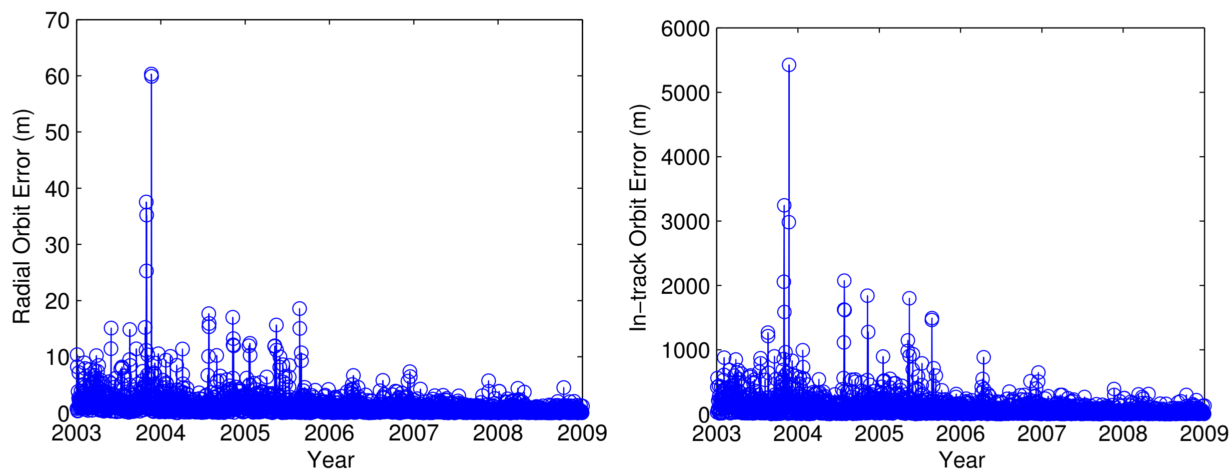


(a) 3-hour Delay Radial (b) 3-hour Delay In-track

Figure 6.2: Maximum orbit differences from each day for a 3 hour delay.



(a) 6-hour Delay Radial (b) 6-hour Delay In-track

Figure 6.3: Maximum orbit differences from each day for a 6 hour delay.

Table 6.1: RMS of orbit differences for density delays

Delay (h)	Radial (m)	In-track (m)
1	0.6762	47.9708
2	1.2214	94.6093
3	1.7078	138.915
4	2.3238	181.152
5	2.8306	220.786
6	3.2998	257.624

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The study was also performed for the advance density profiles over 2003 through 2008. Figure 6.4 depicts the radial and in-track errors for a 3 hour advance. The 6 hour case is also shown in Figure 6.5, again as the worst case scenario. The errors for the advance cases are similar in magnitude to the delayed densities, with the advance being slightly larger on average, but having smaller peak densities. As with the delayed densities, the errors in the radial direction are not relevant compared to the in-track errors. The errors in the in-track direction can reach several kilometers for larger delays, with the October 2003 storm causing an error of almost 5 km for a 6 hour delay.

Table 6.2 contains the RMS of the errors for the advance density profile. These are slightly larger than the delayed density errors, but not by a significant amount. The errors are relevant to the Air Force for 3 hour cases and above. The RMS for a 2 hour advance is almost 97 m, so errors of relevance may be more common for advances of this magnitude.

The errors computed from the different density profiles indicate that large errors of relevance can occur even for the short time offsets during active times. Active times are also the times that larger offsets would be expected to occur more frequently, so the errors during these times are the most relevant. The computed errors also showed that during less geomagnetically active times, even large time offsets do not present large orbit errors. While an occasional spike can occur, they typically remain below errors of relevance. Also, less active times will typically present smaller time offsets, meaning that the larger errors would not be as frequent during these times.

Table 6.2: RMS of orbit differences for density advances

Delay (h)	Radial (m)	In-track (m)
1	0.6702	48.7002
2	1.2093	97.7480
3	1.6880	146.100
4	2.2834	193.401
5	2.7740	239.105
6	3.2243	283.245

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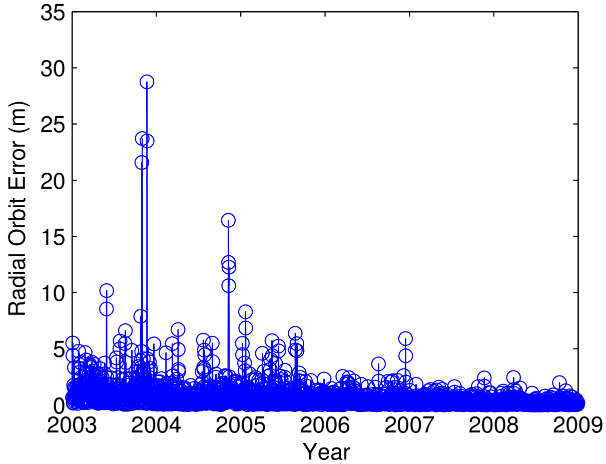
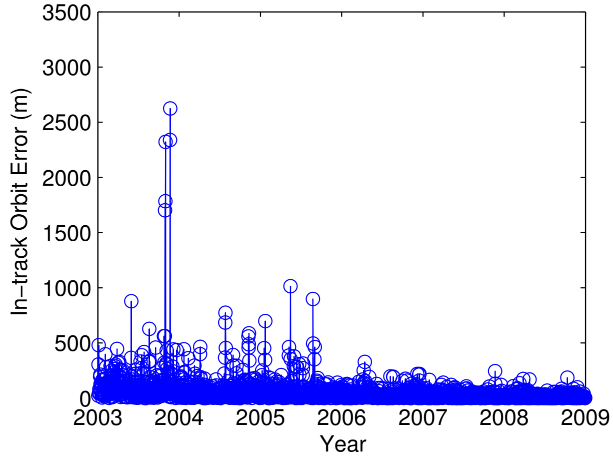
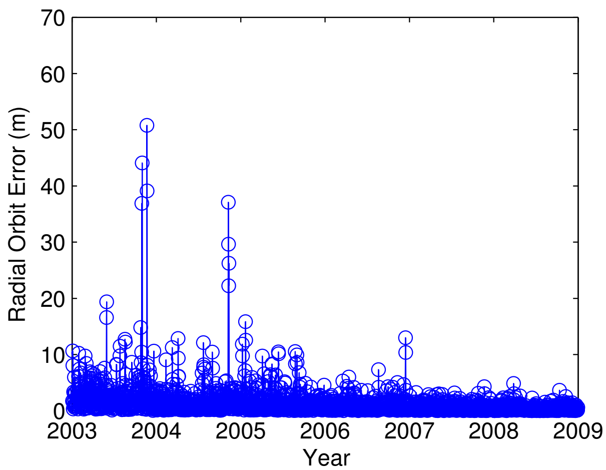


(a) 3-hour Advance Radial

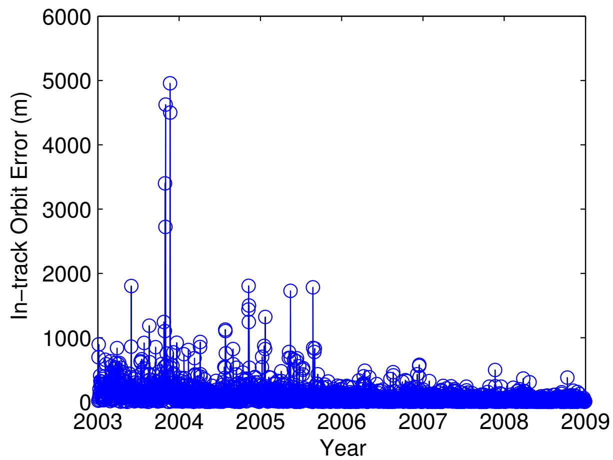


(b) 3-hour Advance In-track

Figure 6.4: Maximum orbit differences from each day for a 3 hour advance.



(a) 6-hour Advance Radial



(b) 6-hour Delay In-track

Figure 6.5: Maximum orbit differences from each day for a 6 hour delay.

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Chapter 7

Conclusion and Future Work

This work examines the effects of time shifts in density models. The JB2008 and NRLMSISE-00 models are the models which are examined, and brief descriptions of each are given. Truth data is taken from densities computed from observations made by the CHAMP satellite. Typical time shifts in density are observed by comparing peak densities computed by the models to the CHAMP densities during geomagnetic storm times. It was shown that the the time offsets can range from 1 to 6 hours, with shifts from 1 to 3 hours being the most common.

Briefly examined were the effects of introducing time delays into an analytical density model. A spacecraft was integrated through an orbit where it encounters a specified density increase at a certain time. A second spacecraft was integrated through the same orbit, but encounters the density increase at a later time. It was shown that delays of a few hours cause errors on the order of tens of meters for this analytical model. It was also shown that decreasing the spacecraft's altitude will increase the orbit error.

Model densities were computed using best available inputs to each model, and these densities were used to compute a satellite orbit over 24 hours. The CHAMP densities were used to compute a similar satellite orbit, and the results were compared to the satellite orbit computed using the model densities. This study was performed for each that CHAMP densities were available for the years 2003 through 2008. It was seen that errors in orbit position can reach up to 8 km in the in-track direction for the NRLMSISE-00 model, and up to 6 km for the JB2008 model. The largest errors occur during times of high geomagnetic activity, with the largest one occurring during a

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large storm in October 2003. In general, the JB2008 was shown to perform better with the best available inputs. The errors seen were shown to be of concern to the Air Force, as well as for the purpose of conjunction assessment.

The effects of time shifts on the models were also examined. A satellite was integrated using best available model inputs and this was taken as truth. A second satellite was integrated using time shifted inputs by 1 to 6 hours either forwards or backwards. It was shown that the errors could reach several kilometers for larger time shifts. The largest errors again occurred during the times of high geomagnetic activity. It was shown that the NRLMSISE-00 model performs better when time shifts are introduced. It is believed that this is because the time shifts have more of an effect on the JB2008 densities, as this model uses hourly geomagnetic indices while the NRLMSISE-00 model uses three hourly inputs.

Finally, the effects of time shifts on real world densities were examined. This was done by smoothing the CHAMP densities to remove short-term orbital variations, and integrating a satellite through this density profile. A second satellite was again integrated, this time using a time shifted density, shifted by a number of hours in either direction. The results from this study were shown to be similar to what was seen in the delayed models, with the largest errors occurring during times of high activity, and the maximum errors reaching a few kilometers. As with the previous studies, the errors were shown to be of significance for the applications mentioned here.

Several opportunities are available for future work in this area. For one, more active years could be examined. Only 2003 was a highly active year, and the others were much less active. If data was obtained for solar maximum times, the density variability would be greater. Also, the same study could be performed for satellites at different altitudes, as it was shown that orbit errors will increase as satellite height decreases. Finally, the study could be performed for other density models.

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