Journal of Global Positioning Systems (2010)
Vol.9, No.2 :104-111
DOI: 10.5081/jgps.9.2.104

A New Concept of Real Time Improvement of Atmospheric Mass Density Models and Its Validation Using CHAMP GPS-Derived Precision Orbit Data

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Abstract

This paper proposes a new concept of real-time improvement of atmospheric mass density models (AMDM) using space tracking data aiming at better orbit prediction accuracy for low latitude earth-orbiting (LEO) space objects. Preliminary experiments using CHAMP GPS-derived precise orbit solution data have demonstrated extremely encouraging and promising results in the error reductions of orbit prediction for 3 days. This suggests that an order of error reduction is achievable by proper fine-tuning of the algorithms.

Keywords: atmospheric mass density modeling; space debris; orbit prediction.

1. Introduction

Space surveillance and space situational awareness are becoming a priority in the space industry, following the release of the National Space Policy of the United States of American (US President Office, 2010). One of the technical foundations required for better services in the space surveillance and space situational awareness is the comprehensive debris tracking and accurate orbital information. The importance of reliable space collision warning, a key aspect of the space situational awareness services, is evidenced by the collision between Iridium 33 and Kosmos 2251 at an altitude of 789km on February 10, 2009 (NASA Orbital Debris Quarterly News, 2009), the first space collision involving an operational spacecraft. If the orbital information of both objects was known accurately, the collision, which generated more than 1600 catalogued and hundreds more uncatalogued objects in the LEO orbit region (Johnson, 2010), could have been avoided by orbital manoeuvres of Iridium 33 satellite. These accidently generated debris objects have increased the danger of space collisions with operational spacecrafts. NASA reported 9 orbital manoeuvres of its operational spacecrafts to avoid space collision in 2009, with only two of them being related to the intact objects, other seven to debris objects (NASA Orbital Debris Quarterly News, 2010). Following the collision between Iridium 33 and Kosmos 2251, and the deliberate destruction of Fengyun-1C satellite, the probability of collisions between debris in the LEO orbital region has increased dramatically.

The inaccuracy of existing atmospheric mass density models (AMDM) has been recognised as the main source causing large errors in the orbit predictions of low altitude space debris objects. Until recently, progresses in improving AMDM accuracy have been made mainly in two ways. The first effort is the correction strategy, represented by the HASDM method (Storz et al., 2005), which determines corrections to mass densities computed from a base model. The accuracy of the final density could be as high as 5% depending on the quality and distributions of the tracking data of the calibration satellites. The second effort is in the improvement of the absolute density model, the latest being JB2008 model (Bowman et al., 2008) and its accuracy is about 10%. In either way, the accuracy improvement is significant, since the accuracy of the widely used models, such as Jacchia 71 (Jacchia, 1971) and MSIS86 (Hedin, 1987), is usually stated at the level of 15% relative accuracy.

An accurate new atmospheric mass density model is the ultimate goal for researchers in the areas of atmospheric physics and astrodynamics, and this could be a long way ahead. All the correction methods, which are results of the efforts in the last decade, have a similar accuracy and appear hard to be further improved (O'Brien and Sang, 2006a). Imminent applications requiring better orbit predictions of debris objects have driven our researches in improving the ADMD accuracy. One of such applications is the unaided laser ranging of LEO debris objects, for which 1-2% relative accuracy of the coefficients of a base density model is required (Sang and Smith, 2010).

In this paper, a new method of real time accuracy improvement of a base density model using space tracking data is proposed. The idea is based on the modification of the model coefficients so that the model with the modified coefficients fits into the space tracking data. The theoretical background for the new method will be discussed first. New algorithms are then developed with DTM78 model (Barlier et al., 1978) used as the base model. Preliminary results using CHAMP GPS data are presented to demonstrate the effectiveness of the new method in reducing orbit prediction errors. Some conclusions and recommendations for future research are discussed.

2. Atmospheric Mass Density Modeling and Its Improvement

It is generally agreed that the accuracy of the density computed from most atmospheric mass density models is about 15%. For example, unattached tables of Picone et al (2002) presented the RMS values of residuals of various observations between 14% and 40% in determining the coefficients of the NRLMSISE-00 model. This suggests that, on average, the accuracy of the computed density is about 15-25% for the altitude range 200-400km. For the altitude range 400-800km, the similar results are obtained, although the number of data sets is much less.

There are so many factors that can cause errors in the computed atmospheric mass density. However, all the error sources can be summarized into two basic categories:

- Modeling error: the appropriateness of the model (the mathematical form), which should describe the real physical world of the thermosphere. This is a fundamental problem faced by atmospheric physicist.
- Model coefficient error: assuming that the mathematical form is correct, the estimated coefficients inevitably contain errors due to the limited temporary and spatial availability and quality of the observation data.

In-depth understanding of detailed physics-chemistry features of the atmospheric temperature and mass density has been a challenging task. There have been two approaches: one is in the theoretical developments (e.g., Izakov, 1971), the other focuses on the observation-based inferences (e.g., Alcayde, 1974; Laneve et al, 1997; Liu et al, 2005).

Both the atmospheric temperature and mass density exhibit lots of similar features. The most significant one is they vary exponentially with the altitude. Other affecting factors include, taking the MSIS86 model (Hedin, 1987) as an example, the following:

- Solar activity ($F_{10.7}$);
- Geomagnetic activity (A_p) ;
- Symmetrical annual;
- Symmetrical semi-annual;
- Asymmetrical annual (seasonal);
- Asymmetrical semi-annual;
- Diurnal;
- Semidiurnal;
- Terdiurnal;
- Longitudinal;
- UT; and
- UT/longitude/geomagnetic coupling..

The progresses in the accuracy improvement of the atmospheric mass density model have been surprisingly slow comparing with other areas of scientific advancement, for example, the earth gravitational model. This is partly due to the complex nature of the atmosphere structure and dynamics in the aspects of the temperature and the number densities of atmospheric mass constituents, which is largely caused by interactions between the incident solar activity, geomagnetic activity and atmospheric species. Accurate modeling of the atmospheric mass density would require more advanced understanding of the atmosphere structure and dynamics and their relations with all depending parameters, such as $F_{10.7}$ or $E_{10.7}$ (Tobiska, 2002), or the geomagnetic index K_p / A_p , etc. The full equation systems of the theoretical atmospheric temperature and density models are not analytically solvable; simplifications have to be made to obtain a solution. Various simplifications result in a number of empirical atmosphere temperature and mass density models, such as Jacchia series, DTM series and MSIS series. For the reasons stated above, all the empirical models contain errors.

In precise orbit determinations of space objects, the errors of the mass densities are usually accommodated by introducing a number of air drag coefficients, which are estimated along with other parameters, such as satellite position and velocity vectors at some epochs, and solar radiation pressure coefficients. By doing so, the observation residuals are usually much smaller than those obtained if only a single air drag coefficient is estimated.

The precise orbit determinations are only possible if the satellite of interest has tracking data of sufficient accuracy and dense distribution both temporally and spatially. When we deal with the orbit determinations, and in particular predictions, of debris objects, we do not have that luxury to fine tune force model parameters. Usually it is assumed that the force models utilised are accurate.

The methods of correction, which include the HASDM, NCY method (Granholm et al, 2002; Yurasov et al, 2004) and EOS Shell method (O'Brien and Sang, 2006b), aim to determine the corrections to (or errors of) densities computed from a base model using space tracking data of about 70-80 calibration satellites spatially well distributed. The algorithms and software can be easily implemented in a real-time manner. The mathematical formulations of the three correction methods are substantially different because of different assumptions regarding the models of the corrections. There are no further deliberations given by the authors of these methods on the theories under which the correction algorithms are developed.

2.1 Real Time Modification of Model Coefficients Using Space Tracking Data

A new and more straightforward method of improving the accuracy of a density model, for the purpose of better short-term orbit prediction accuracy, is proposed here. This new method involves a near-real time modification of model coefficients of a base density model using space tracking data.

The rationale behind this strategy is stated below. All the existing individual density models have performed well on average over a long period of time, say one year or longer. Over a short period of a few days, the computed mass density from a particular model (the base model) usually exhibits some systematic bias (although such systematic patterns are unknown and may be varying wildly) against the true density value. Such biases reflect the dynamic nature of the atmospheric mass density, and may be difficult to be modeled. Instead of modeling the density errors (by the correction methods) of the base model, the base model itself is adjusted to fit into the space tracking data. This adjustment occurs on the model coefficients, i.e., the model coefficients are modified such that the model is best fit to the tracking data.

The modification of the density model coefficients can be carried out in a standard satellite orbit determination procedure, where, the model coefficients are estimated along with other parameters, which could include air drag coefficients. Therefore, a real time implementation of the method in an existing satellite orbit determination system is quite straightforward.

This new method makes only a very simple and general assumption about the dynamics of the atmospheric mass density modeling:

> ***The only assumption is that****, by modifying the coefficients of a base model, the model will be fit into the tracking data, which is the true reflection of the orbital dynamics of space objects being tracked, which in turn is affected by the dynamics of the atmospheric mass density. In fact, with proper techniques, a data set could be, almost always, modeled, or a model could be fit into a data set. Other than this, no other assumption is made in the concept formation and the following algorithm development.*

If the dynamics of the mass density has a tendency over a time period, which is usually the case, then, a potentially major advantage of this new method over the correction methods is that the model with the modified coefficients may perform better in the orbit predictions of space debris objects. This is probably the most imminent objective of the researches on the mass density model improvements for practical applications.

3. Algorithm Development

In the following algorithm development, the DTM78 model is used as the base model. It is easily seen that, the algorithm development procedure is very general and can be easily applied to all empirical models.

The equations of motion of an earth-orbiting object are usually described in a simplified form

$$\ddot{\vec{\mathbf{r}}} = \vec{\mathbf{f}} \tag{1}$$

where $\vec{\mathbf{r}}$ is the position vector of the object, and $\vec{\mathbf{f}}$ is the force per unit of mass exerted on the object. The force usually includes the earth gravity (including tidal effects) $\vec{\mathbf{a}}_{EG}$, the third-body gravitational forces $\vec{\mathbf{a}}_{TBG}$, the solar and earth radiation pressures $\vec{\mathbf{a}}_P$, and the atmospheric drag $\vec{\mathbf{a}}_{Drag}$ etc. That is,

$$\vec{\mathbf{f}} = \vec{\mathbf{a}}_{EG} + \vec{\mathbf{a}}_{TBG} + \vec{\mathbf{a}}_P + \vec{\mathbf{a}}_{Drag} + \cdots \tag{2}$$

The drag is computed using

$$\vec{\mathbf{a}}_{Drag} = -\frac{1}{2} C_D \frac{A}{m} \rho v \vec{\mathbf{v}} \tag{3}$$

where C_D is the drag coefficient of the object, $\frac{A}{m}$ is the area-to-mass ratio, v is the magnitude of the velocity vector $\vec{\mathbf{v}}$, and ρ is the atmospheric mass density computed from an empirical model, here the DTM78 model.

For the DTM78 model, the atmospheric temperature is first computed, and then the number densities of 4 mass constituents. The temperature and all of the 4 constituents (Helium, Oxygen, Nitrogen and Hydrogen) take the equation of the same form consisting of

Legendre polynomials. The equation has 36 nominal coefficients (value of some coefficients may be zero). Also, there are five coefficients (in fact, only two are non-zero) for the thermal diffusion, one for temperature at the altitude of 120km, and one for the temperature gradient. In total, there are 187 nominal coefficients, which are considered to be estimable. In a simplified mathematical form, we have

$$\rho = \rho(t, \vec{\mathbf{r}}, \vec{\mathbf{b}}, \vec{\mathbf{c}}) \qquad (4)$$

where vector $\vec{\mathbf{b}}$ contains the position of the Sun and geomagnetic index K_p and solar flux index $F_{10.7}$ and its mean value over the 81 days centred at the day. The vector $\vec{\mathbf{c}}$ contains all the 187 coefficients of the model.

To estimate the model coefficients with a least-squares or Kalman filtering approaches, the partial derivatives of observations, such as GPS derived position vector of a space object, have to be computed. The partial derivatives are computed by numerical integration of the variational equations for the to-be-estimated parameters, of which the model coefficients are part. For example, the variational equations of c_0, the first coefficient in the function computing the thermospheric temperature, are

$$\frac{\partial \ddot{\vec{\mathbf{r}}}}{\partial c_0} = -\frac{1}{2} C_D \frac{A}{m} v\vec{\mathbf{v}} \frac{\partial \rho}{\partial c_0} \qquad (5)$$

where $\frac{\partial \rho}{\partial c_0}$ can be computed analytically from the equation systems of the DTM78 model, or numerically if preferred.

Popular estimation techniques, such as weighted constraints for some or all of the model coefficients, can be applied. The fine-tuning of the algorithms might be model specific, and probably dependent on the number, distribution, accuracy, and type (range, angles, position, or combination of them) of observations. In the current development of the algorithm using the DTM78 model as the base density model, each of the non-zero coefficients is treated equally. In the future, a careful sensitivity analysis of the model coefficients may help in the algorithm fine-tuning. These will be part of our future investigations.

4. Validation Using CHAMP GPS Data

CHAMP GPS-derived precise orbit solution data is used to perform the validation of the concept and algorithms developed above. Bear in mind that the main purpose of the real time modification of the model coefficients is to improve the orbit prediction accuracy for debris objects. The CHAMP GPS orbit data is downloaded from the CHAMP ISDC (Information Systems and Data Center) website (http://isdc.gfz-potsdam.de/). The rapid science orbit data is used in our experiments.

The basic procedure of a computation run consists of the orbit determination of a 3-day arc and prediction for 10 days, and the calculation of the orbit prediction errors using GPS orbit data as "truth". For the same data set, one run is carried out without the modification of the DTM78 model coefficients, and another with the model coefficient modified.

4.1 Orbit Determination

To reflect the reality of debris orbit determination and prediction, that is, the observations are usually sparse and not accurate, we do not use a full set of the original GPS positioning data. In fact, the whole continuous orbit is cut into many consecutive short arcs each being 6 minutes long. Then, only a small number of these short arcs are used, with the interval between used short arcs being set 2 hours. The interval between two consecutive data points in a short arc is set 1 minute. Therefore, on a three day orbit determination arc, there are about 720 data points, each with X, Y and Z coordinates used as observations, and the velocity components not used.

Because the GPS position data is very accurate, the positional components are intentionally corrupted by adding random Gaussian errors of mean zero and standard deviation 20m. This is to reflect the observation accuracy of debris objects with Radar or optical tracking techniques. Laser ranging of debris objects can be accurate to the meter level.

The forces or the force models in the orbit computation include:

- Gravitational model: JGM-3 (Tapley et al., 1996);
- Ocean tidal model: CSR 3.0 (Eanes and Bettadpur, 1995);
- Solid Earth tidal model: Chapter 6, IERS Technical Note 21 (McCarthy, 1996);
- Third body gravitational forces: Sun, Moon, and all solar planets with DE200 planetary ephemeris;
- Atmospheric drag: satellite mass 522kg, and cross-sectional area 0.72 m^2. We intentionally do not use CHAMP's panel model to calculate the cross-sectional area of the satellite; and
- Solar and Earth radiation pressures: mass 522kg, and cross-sectional area 0.72 m^2.

The unknowns in the orbit determination include the position and velocity vectors at the initial epoch of the 3 day arc; a single atmospheric drag coefficient, and a single solar radiation pressure coefficient. Of course, when the coefficients of the DTM78 model are to be modified, the unknowns include these model coefficients.

The orbit determination is carried out in a batch least-squares way and is terminated when the change in the position components of the initial epoch from the previous iteration is smaller than 1m. When the coefficients of the DTM78 model are estimated, not all newly estimated coefficients will be used. We ask the difference between the new and old values less than some pre-set limit, for example, 30% of the old value.

4.2 Orbit Prediction

When the orbit determination process is converged, the orbit is predicted 10 days into the future, and if available, the newly modified coefficients of the DTM78 model are used.

The predicted positions are differenced with the ISDC-downloaded positions to obtain the orbit prediction errors. The along track, cross track and radial biases are used to highlight the significance of improving the atmospheric mass density models.

4.3 Results

Validation computations are conducted from the orbit determinations of 79 3-day arcs each starting at the midnight epochs (UTC time) between 02 January and 21 March, 2009, and subsequent orbit predictions. The residuals of the observations (i.e. the corrupted GPS position components X, Y and Z) from the orbit determinations are generally in tens of meters. Typical examples of these residuals are shown in Figure 1.

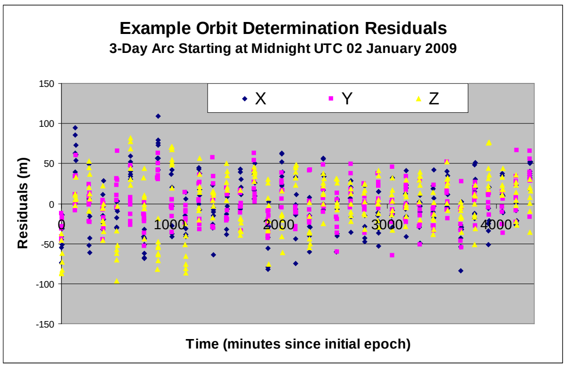

Figure 1: An Example of Typical Orbit Determination Residuals

As mentioned earlier, when the density model coefficients are estimated, the corrections applied to the coefficients are restricted to be smaller than a factor of the current magnitudes of the coefficients. For example, when the factor is set 0.3 for orbit determination of the 3-day arc starting at the midnight on 2 January 2009, the total (or accumulated) corrections applied after the computation convergence, in percentage, are shown in Figure 2. We can see that, most of the corrections are zero (the corresponding coefficients are not corrected). Because, in each iteration of the least squares computation, when the estimated correction to a model coefficient, in terms of the percentage with respect to the value of the corresponding coefficient, is larger than the preset factor (30%), no correction is applied to the coefficient. But for some coefficients, the total corrections can be as large as 60-80% of the original values.

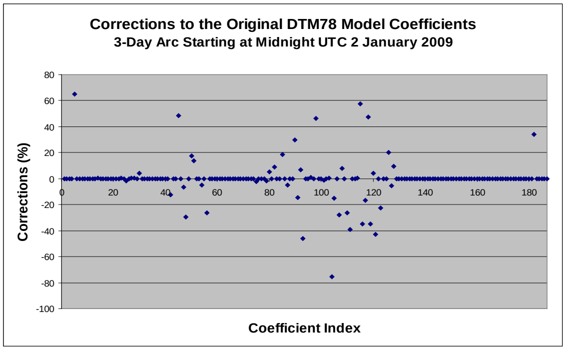

Figure 2: An Example of Relative Corrections to the Original DTM78 Model Coefficients

The main objective of the real time density modeling is to improve the accuracy of the short-term orbit predictions. Thus, we compare the prediction errors obtained from using the DTM78 model with the original coefficients and the modified coefficients, respectively. Such a comparison is made between the along track biases, since, large density model errors usually results in large along track biases. An example of the magnitudes of the along track, cross track and radial biases is shown in Figure 3, from which we see that, at the end of 3 day prediction period, the cross track and radial biases are almost negligible compared with the along track bias.

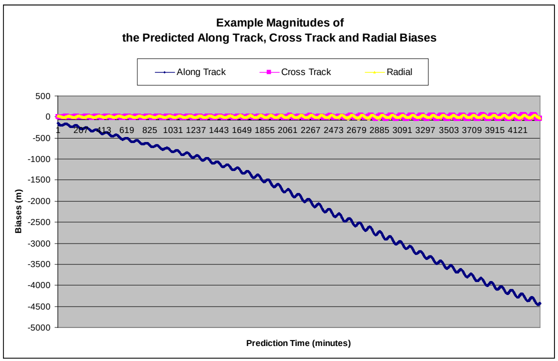

Figure 3: An Example of the Magnitudes of the Predicted Along Track, Cross Track and Radial Biases

The comparison results are represented by the ratio of the along track biases at the end of 3 day prediction periods, obtained with the modified and original model coefficients, respectively. A ratio value less than 1 means that the accuracy of the prediction is improved. All the 79 ratios (recall that 79 3-day arcs are processed for the orbit determinations and estimation of the density model coefficients, and subsequent orbit predictions) are shown in Figure 4. Among 79 ratios, 54 have the values less than 1. The remaining 25 ratios have values larger than 1 indicating that the prediction accuracy deteriorates when the modified model coefficients are used. An example of bias ratio lager than 1 is shown in Figure 5, where it is seen the along track bias at the end of 3-day prediction period obtained using the original model coefficients is smaller than that using the modified model coefficients (1488m against 1957m). However, the overall results suggest that the real time improvement of the DTM78 model can be achieved.

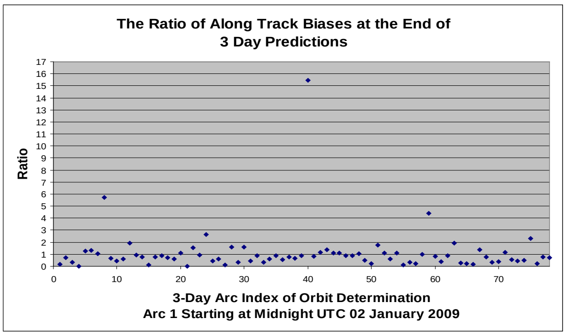

Figure4: Ratios of Along Track Biases at the End of 3 Day Prediction Period

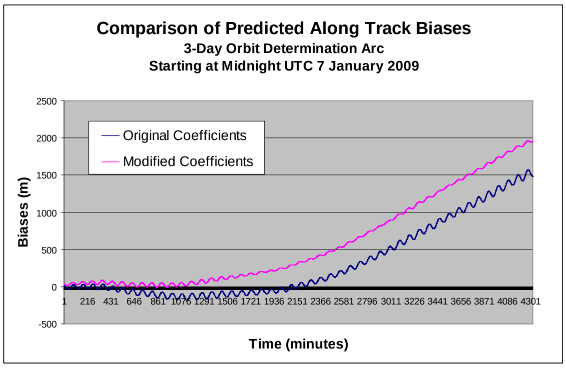

Figure 5: Comparison of Predicted Along Track Biases for 3 Days – Example of Worsening

Figure 6 shows an example of the reduction of the predicted along track biases when the model with the modified coefficients is used. At the end of the 3 day prediction period following the orbit determination of the 3 day arc starting at the midnight on 16 January 2009, the along track bias is reduced from -2859m to -307m, obtained respectively using the original and modified coefficients with the DTM78 model.

In a further demonstration of the effectiveness of this new concept on the accuracy improvement of the orbit prediction, Figure 7 shows a comparison of the predicted along track biases for 10 days following the orbit determination of the 3 day arc starting at the midnight on 3 January 2009. It is seen that, after reaching the maximum value 2275m, the along track bias, obtained using the modified model coefficients, is about -110m at the end of the 10 day prediction time. For the bias using the original coefficients, its magnitude increases to more than 15000m almost monotonically, a property common to almost all the density models.

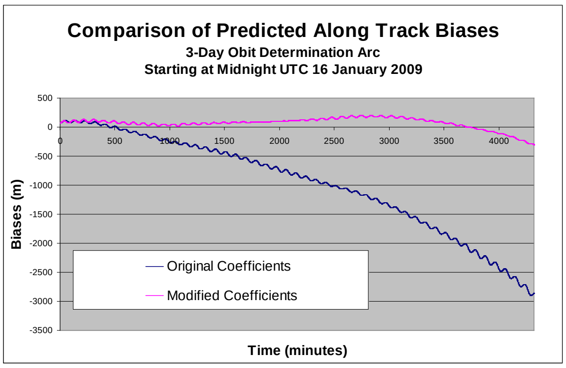

Figure 6: Comparison of Predicted Along Track Biases for 3 Days – Example of Improving

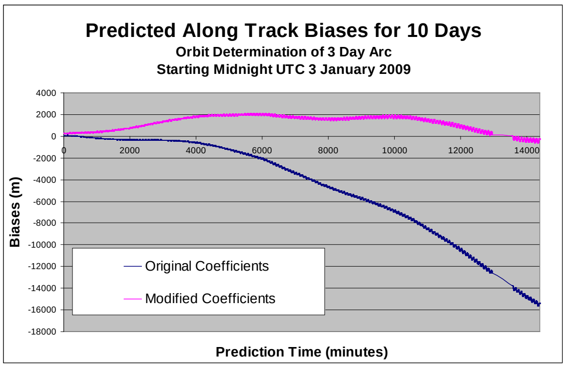

Figure 7: Comparison of Predicted Along Track Biases for 10 Days

In summary, the above preliminary small-scale investigations have shown that the concept of the real time modification of the atmospheric mass density model coefficients is not only feasible but also valid and effective in reducing the orbit prediction errors.

5. Conclusions

In this paper, the concept of the real time improvement of the atmospheric mass density models by modifying the model coefficients using space tracking data is proposed first. The aim of the new method is to increase the short term orbit prediction accuracy, which is critically important to the space situational awareness. The algorithm can be easily implemented within the frame of any satellite orbit determination software. The validation of the concept has been performed with the DTM78 model and the CHAMP GPS positioning data.

It has demonstrated that the orbit prediction errors in the along track direction over the prediction periods of 3 days and 10 days respectively have been significantly reduced. The results so far are encouraging and warranted for further studies.

Further validations are suggested since only a single satellite scenario is tested in this paper. It is expected the concept will hold true in a global scale and of course more extensive experiments involving multiple satellites and various tracking data are required. The fine-tuning of the algorithm, and development of measures for controlling qualities of results in real time, are merely two of many research areas.

Acknowledgement

This research is partially supported by the Australian Government through the Australian Space Research Program funded project “Platform Technologies for Space, Atmosphere and Climate”, and Australia Research Council Linkage project “Precise Atmospheric Density Correction Model Using Space Tracking Data for Accurate Debris Surveillance and Collision Warning”.

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Biography

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