ANALYSIS OF THE GRAVITY MODELS IMPACT ON LEO SATELLITE ORBIT PREDICTION

Yonggai Zhuang[1], Lei Wang[2*]

1. School of Journalism and Mass Communication, Wuhan University
2. State Key Laboratory of Information Engineering in Surveying, mapping and remote sense, Wuhan University
Contact: Lei.wang@whu.edu.cn

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ABSTRACT:

Non-spherical gravity plays a crucial role in the LEO satellite orbit determination and prediction. In recent years, several new gravity models have been proposed with more comprehensive ground and space-borne data. The impact of the gravity models has been extensively studied while its impact on the orbit prediction has not attracted enough attention. With the risen of the mega LEO constellation, new applications such as the LEO navigation requires real-time precise orbit, which increases the importance of the precise orbit prediction. In this study, we selected six popular gravity models, namely JGM3, EGM2008, EGM96, EIGEN2, GL04C, and GGM03S, and compared their performance in different LEO orbit predictions. The comparison results indicate that there is no single optimal gravity model for all LEO orbit prediction scenarios. For short-term prediction, JGM3、EGM2008、GL04C models perform better while in long-term prediction JGM3、EGM96、EIGEN2 have more potential. The results also reveal that the optimal model changed with time. In addition, the impact of the gravity order on the orbit prediction is investigated, the results indicate that for satellites with lower orbital heights, the gravitational field order required to achieve a certain truncation error is higher than for satellites with higher orbital heights. The authors also explore the effect of gravitational field-associated permanent tides on orbital prediction. In one day, for satellites with an orbital altitude of about 970km, the effect of permanent tides on 3D RMS is 6.92m; for satellites around 710km, the effect of permanent tides on 3D RMS is 4.20m; for satellites around 970km, the effect of permanent tides on 3D RMS is 2.07 m.

1. INTRODUCTION

LEO orbit prediction is of great significance for real-time satellite operation, such as mission planning, orbit maneuver. and real-time navigation (X. Guo et al., 2021). In recent years, navigation from LEO become a hot research topic, which requires high precision, real-time satellite ephemeris (L. Wang et al., 2020). As known. the accuracy of satellite ephemeris depends on the final positioning performance, and the predicted orbit is essential to obtain real-time ephemeris. Although there has been some research on LEO navigation, how to obtain the optimal predicted orbit has not attracted enough attention.

LEO orbit prediction relies on numerical integration of forces, so the key to obtaining high accuracy orbit prediction is precisely modeling the forces. LEO satellite suffers both conservative and non-conservative forces, and the earth's gravity is the most important conservative force for LEO satellites, which can be several orders higher than the rest of perturb forces. In this study. we quantitatively analyzed the impact of gravity models, the optimal gravity model orders and permanent tide impact on the LEO orbit prediction.

Although there have been many global gravity models, they can be divided into two classes via gravity observing technology. The first generation gravity model is represented by JGM3 (Joint Gravity Model 3) and EGM96. The gravity inversion of these models is mainly realized by satellite altimetry combined with SLR(satellite laser ranging) and ground gravity data. The second-generation gravity models rely on the space-borne gravity observing technologies, such as satellite-satellite tracking (SST) and Satellite Gravity Gradiometry (SGG) since a series of gravity-observing were launched, such as the GRACE mission, CHAMP mission, GOCE mission and others. These satellites provide more homogenous global gravity observations and lead to a breakthrough of the gravitational models. The representative second-generation gravity models are EGM2008, EIGEN2, GGM03S, etc.

There have been a few researchers who examined the impact of gravity models on the satellite orbit determination accuracy. Z. Wang and Zhang (2016) compared four gravitational field models with the simplified dynamics and concluded that EGM2008 and EIGEN-6C4 are better accurate than JGM3 and EGM96. J. Guo, Qin, Kong, and Li (2012) used 3 days of DORIS data to compare the accuracy of the five gravity models with different orders; Based on SLR data, H. Wang, Zhao, Zhang, Zhan, and Yu (2016) addressed that the accuracy of the four new models after 2000 is increased by about 12%~47% for orbit determination and 63% for orbit prediction; Sośnica, Thaller, Jäggi, Dach, and Beutler (2012) used LAGEOS SLR data to combine the orbit determination error calculated by the multiplex gravity model with the specific value of gravitational field order terms, explaining the negative effect of C20 modeling and the conclusion that LAGEOS orbit is insensitive to the choice of the gravity field. However, the impact of gravity models on the LEO orbit prediction has not attracted enough attention. H. Wang et al. (2016) only compared the GRACE data for one day, which means it is of limited convincing. In orbit determination, the orbit accuracy depends on both dynamic models and GNSS/SLR observations, so the dynamic errors can be somehow mitigated by introducing pseudo-stochastic parameters or empirical acceleration.

Meanwhile, orbit prediction only relies on the dynamic force integration and more vulnerable to dynamic model errors.

In satellite orbit prediction, gravity models, different orbit altitudes, and different prediction times produce many interesting problems. The selection of the gravity field model with different orbital heights, the effect of the model changes with the prediction time, and the reasons for the good model prediction effect are all worth exploring.

In addition to these more conventional problems, the author also found a gravity field processing-related problem in orbit prediction. Gravity models have two types, zero-tide and tide-free, requiring C20 term correction in the treatment. However, the relevant treatment has long been controversial in the GPS computation field (Poutanen, Vermeer, & Maikinen, 1996). In this context, it is also a worthy question whether the permanent tidal correction is effective in improving the accuracy of orbital prediction.

Based on the above problems, the rest of the paper is organized as follows. Section 2 introduces the theory of LEO prediction. The third section designs three sets of contrasts for the gravitational field based on different satellite data. In Section 4, the author summarizes the results of the correlation analysis and puts forward his own opinions and suggestions on the selection and treatment of the gravity field in LEO orbit prediction.

2. LEO ORBIT PREDICTION

LEO orbit prediction relies on numerical integration of forces, so the key to obtaining high accuracy orbit prediction is precisely modeling the forces. Precisely modeling the forces requires analysis of the dynamic model.

2.1 Dynamic Model

Satellites are subjected to multiple external forces while operating around the earth Role, overall, its kinetic model can be divided into two categories. The corresponding differential equations of motion can be written as:

$$\ddot{r} = R_0 + R_\ell , \tag{1}$$

where R_0 is the perturbative acceleration of the satellite caused by conservative forces, which include the earth's gravity, sun and moon N body attraction, tidal effects, etc. R_ℓ is the perturbative acceleration of the satellite caused by non-conservative forces, which include the atmospheric drag, solar radiation pressure, etc. The earth's gravity is the primary attraction force for the LEO satellites, which is several orders higher than the rest perturb forces and difficult to describe. Atmospheric drag is the largest non-conservative force, which has a long-term impact on the satellite accuracy in the along-track direction. In prediction, it is mainly corrected with an empirical atmospheric drag model. Sun-moon N-body gravity is historically calculated in orbit prediction by combining JPL stars. solar radiation pressure is a kind of non-conservative force and is calculated mainly by modeling satellite surfaces in orbit prediction.

Tidal is closely related to the gravity of the sun and moon N body and the earth gravity. Under the gravity of the sun and moon N body, the earth's mass redistribution and shape change, which makes the earth's gravitational field change, which produces additional force to the satellite. The tidel effect is often implemented by correcting the gravitational field in prediction.

This paper focuses on gravitational field models and the permanent tide related to gravity.

2.2 Gravity Theory

The gravitational position of the Earth to the external space points is expressed in the form of the spherical harmonic coefficient expansion as (F. Wang, 2006):

$$U(r,\beta,\lambda)=\frac{GM}{\mathrm{r}}\left[1+\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{\mathrm{a_e}}{\mathrm{r}}\right)^{l}\overline{P}(\sin\beta)\left[\overline{C_{lm}}\cos \mathrm{m}\lambda+\overline{S_{lm}}\sin m\lambda\right]\right], \tag{2}$$

where GM is the product of the gravitational constant and mass of the Earth, r is reference radius , β is geocentric latitude, λ is geocentric longitude, $\overline{P}(\sin\beta)$ is the fully normalized Legendre functions , $\overline{C_{lm}}$ and $\overline{S_{lm}}$ are the fully normalized Stokes's coefficients provided by gravity models. The first term of the equation is central gravity and the second term is non-spherical gravity.

Further, the non-spherical gravitational acceleration can be calculated using the gradient of the non-spherical gravitational bit function, so the perturbation acceleration of the non-spherical gravity can be expressed as:

$$\ddot{x} = \frac{\partial U}{\partial \mathrm{r}}\frac{\partial \mathrm{r}}{\partial \mathrm{x}}+\frac{\partial U}{\partial \beta}\frac{\partial \beta}{\partial \mathrm{x}}+\frac{\partial U}{\partial \lambda}\frac{\partial \lambda}{\partial \mathrm{x}} , \tag{3}$$

$$\ddot{y} = \frac{\partial U}{\partial \mathrm{r}}\frac{\partial \mathrm{r}}{\partial \mathrm{y}}+\frac{\partial U}{\partial \beta}\frac{\partial \beta}{\partial \mathrm{y}}+\frac{\partial U}{\partial \lambda}\frac{\partial \lambda}{\partial \mathrm{y}} , \tag{4}$$

$$\ddot{z} = \frac{\partial U}{\partial \mathrm{r}}\frac{\partial \mathrm{r}}{\partial \mathrm{z}}+\frac{\partial U}{\partial \beta}\frac{\partial \beta}{\partial \mathrm{z}}+\frac{\partial U}{\partial \lambda}\frac{\partial \lambda}{\partial \mathrm{z}} , \tag{5}$$

where x, y, and z refer to the three-dimensional coordinates of a satellite in the Earth-solid system, and $\ddot{x}$, $\ddot{y}$, $\ddot{z}$ refer to the acceleration generated by the Earth's gravitational field in the Earth-solid system. Thus, the perturbation acceleration in the solid system is obtained, after precession, nutation and polar motion correction, and the perturbation acceleration of non-spherical gravity can be expressed as:

$$\ddot{R} = PN\Theta\varpi\ddot{r} , \tag{6}$$

where P is the rotation matrix for precession， N is the rotation matrix for nutation, Θ is the rotation matrix for Greenwich sidereal time， ϖ is the rotation matrix for polar motion, $\ddot{R}$ is the acceleration in the inertial system, $\ddot{r}$ is the acceleration under the earth-fixed coordinate system.

For different gravitational models, the perturbation acceleration calculated in the orbital prediction also varies due to the different values of $\overline{C_{lm}}$ and $\overline{S_{lm}}$. This difference further affects the result of the prediction.

2.3 Permanent Tide Correction

There are two tide correction modes in the gravity models: zero-tide and tide-free, which correspond to tidal-related concepts.

The tidal potential contains both time-independent (permanent) and time-dependent parts. Satellite orbits are affected by displacements associated with solid Earth deformations produced by the tidal potential. In the process of solving the static gravity field, some models adopt the way of tide-free, and it has removed the two parts, some models use zero-tide, just removing the time-dependent part.

According to IERS Convention (2010), for the zero-tide type of GGM03S, JGM3, because the tidal model has calculated the total contribution of the tide in the calculation, the repeated calculation of the process of the gravitational field needs to be avoided, which means before the treatment of tide model, eliminating the effects of the permanent tide must be carried out first to convert the zero-tide model to a tide-free model. The specific equation can be expressed as follows:

$$C_{20}^{\text{zero-tide}} - \left(4.4228 \times 10^{-8}\right)\left(-0.31460\right)k_{20} = C_{20}^{\text{tide-free}}, \tag{7}$$

where k_{20} is nominal Love number. With this formula, on the one hand, we can observe the help of correcting the C20 term before the tidal model, and on the other hand, we can in turn compare the effect of permanent tides on the gravity field.

Although the C20 corrections are made for zero-tide gravitational field models in Bernese, in many track-related practices, the permanent tidal correction of C20 is often ignored, further leading to zero-tide gravitational field model and tide-free gravitational field model without discrimination in contrast, which has a certain impact on the correlation accuracy of orbit determination and prediction.

2.4 Orbit Prediction

The orbit prediction method adopted in this study is a single point prediction, which does not need to provide long period information in the past time, but only requires the precision satellite ephemeris to provide information about the first epoch, using the satellite equation of motion for numerical integration:

$$\dot{r} = v, \tag{8}$$

$$\dot{v} = -\frac{GMr}{r^3} + R, \tag{9}$$

where r is the position vector under the satellite inertial system, v is the velocity vector of the satellite motion, R represents the sum of the various driving forces of the satellite. According to the state vector(r_0 , v_0) at the previous moment t_0 , the state vector (r_t , v_t) at the next moment t can be obtained by numerical integration.

For autonomous orbit determination and orbit prediction, the common methods of numerical integration are the classical Runge-Kutta method, Runge-Kutta-Fehlberg method and Runge-Kutta-Nystrom method, etc. Their principles are all implemented mainly achieved by indirect reference to the Taylor expansion. To balance the need for efficiency and computational accuracy, the six-order Runge-Kutta integrator is used in LEO orbit prediction.

3. COMPARISON OF GRAVITY MODELS IN LEO ORBIT PREDICTION

3.1 Experiment Setup

In order to compare the performance of different gravity model in orbit prediction, we compared six commonly used gravity models (See Table 1). In general, the paper designs three sets of experiments for different gravity field models, different orders and permant tide impact analysis. The first experiment takes the 70 order as the standard cutoff of each gravity field to observe the short-and long-term prediction accuracy of each gravity model; then, we takes the 10 order as the cutoff error to compare the long-term and short-term performance of the same gravity field under different orders; we also compared the orbital prediction effect before and after C20 correction for the same gravity model to illustrate the effect of permanent tidal correction.

Gravity Models	Highest Order	Tide Mode	Data Sources
Joint Gravity Model 3 (JGM3) (Tapley et al., 1996)	70	zero-tide	integrates SLR data from LAGEOS1, LAGEOS 2, and Stella satellites, Doppler data (DORIS) and GPS data from TOPEX / POSEIDON
Earth Gravitational Model 1996(EGM96)	360	tide-free	TOPEX / POSEIDON, ERS 1, and GEOSAT satellite elevation data, ground gravity anomaly data, as well as more than 30 satellite tracking data (GPS, SLR, DORIS, etc.)
EIGEN2	140	tide-free	half a year of CHAMP satellite tracking data
EIGEN-GL04C	360	tide-free	combined with GRACE (data from February 2003 to July 2005), LAGEOS and ground gravity data
GGM03S	180	zero-tide	four full years of GRACE data to help average annual variations

EGM2008(Pavlis, Holmes, Kenyon, & Factor, 2012)	2190	tide-free	57 months of GRACE data from September 2002 to April 2007

Table 1. Description of different gravity models.

The data used in the study is Precise Science Orbit (PSO) data of LEO satellites. The PSO data used in this study are GRACE (2008-2013), HY-2A (2012-2016), ENVISAT (2008-2012), TerraSAR-X (2009-2013), and Cryosat-2 (2011-2015). All satellite orbits are calculated in the same ground reference frame, and the orbit processing follows IERS CONVENTIONS (2010). In the selected periods, the author predicts from the first ephemeris of January 1 of each year.

To ensure the high accuracy and accuracy of the prediction, all other models adopt high-precision models, where the relevant modified models are shown in Table 2;

Reference frame	International Celestial Reference Frame
Earth gravity field	JGM3, EGM96, EIGEN2, GGM03S, EGM2008, EIGEN-GL04C Tides corrections
Relativistic effect	Post-Newtonian correction
Atmospheric drag model	NRLMSISE-00 Model
Solar radiation pressure	Geometry-dependent projected area Shadow model: Earth eclipse considered
Numerical integrator	6 order Runge-Kutta integrator with 30s step
N-body attraction	JPL DE430

Table 2. Orbit models used in this paper.

To better compare the accuracy of gravity models in orbital prediction, the selected LEO satellites cover different orbital altitude (See Table 3). In the process of prediction (See Figure 1), we use single-point prediction and maintain the consistency of other models, focusing on comparing different models by RMS and prediction error.

LEO satellite	Orbital altitude （km）	Orbital inclination	Launch year
GRACE	480	89.5°	2002
HY-2A	965	99.34°	2011
TerraSAR-X	514	97. 4°	2007
ENVISAT	810	98°	2002
Cryosat-2	710	66°	2010

Table 3. Description of Satellites used in the paper.

Since the article adopts empirical atmospheric parameters, in the long-term prediction or the prediction for low orbital height satellite, it may produce error accumulation problems, further causing the non-accuracy of the contrast. For the short-term prediction or the prediction for higher orbit satellites, 3D-RMS is somehow reasonable, but they are not the best choice in the long-term prediction. Therefore, the RMS and prediction error in the radial direction is used instead of the 3D-RMS in the following comparison.

3.2 Comparison of Different Gravity Field Models

For the comparison of gravity models, the comparison results of long-term and short-term predictions are not consistent.

The authors first compare the prediction results in the short term. The authors performed orbital prediction within 30 minutes for satellites at different orbital heights. The results show that even for satellites with different orbital heights and integrated from the same time point in different years, the results of orbital prediction show similar rules. Within 30 minutes, the 3D-RMS and prediction error of the new generation model is much smaller than those of the old generation model; This corresponds to some articles studying the gravity for orbit prediction, which further illustrates the help of satellite tracking technology to improve the gravity field accuracy.

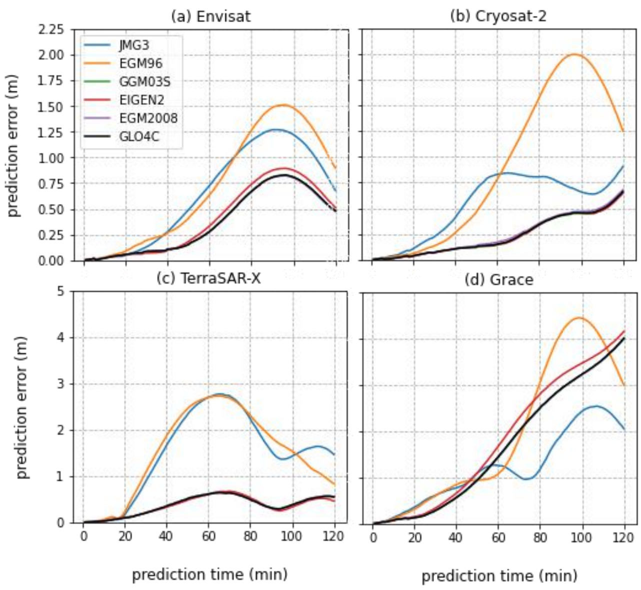

Figure 1. 3D Prediction error with different gravity model.

Extending the prediction time to 120 minutes shows some fluctuations, and the best models for the other three satellites remained consistent except GRACE. For GRACE, two originally poor models, JGM3 and EGM96 models, fluctuate violently and have outperformed several other models at a certain point in time, and this situation did not occur in a unique year.

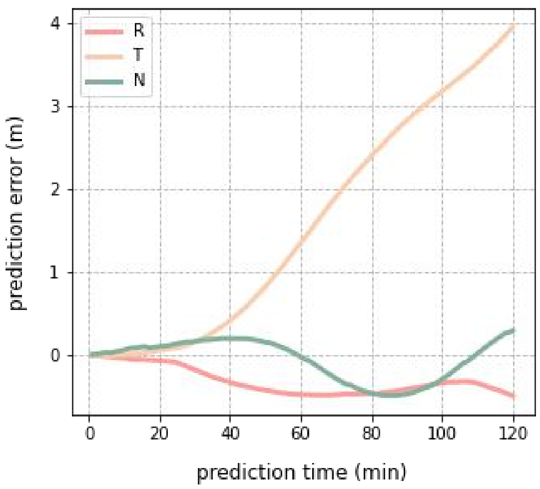

Figure 2. Prediction error in 3 directions of GRACE in 120 minutes prediction.

For this case, the author explains that because GRACE orbit height is low, the inaccurate modeling of other models (such as the atmosphere) will affects the comparison by 3D-RMS (See Figure 2) with the prediction time increases. In such cases, it will be inaccuracy if continued compared by 3D-RMS.

Therefore, the paper changed the comparison method here, and instead used for contrast by RMS in the radial direction. Using the 120-minute RMS in radial direction comparison, the author finds that while the best model for the GRACE satellite predictions shows a fluctuating 3D-RMS at 120 min, fluctuations did not hinder their error size in the radial direction. By RMS in the radial direction， it can be seen that the accuracy of the short-term old generation gravity model (JGM3, EGM96) is far less than the new generation gravity model (GGM03S, etc) and it must be seen that as the height of the orbit decreases, the disturbance increases and the difference between the prediction effect of the new and old gravity field models is further increased.

Gravity field model	Envisat	Cryosat-2	TerraSAR -X	GRACE
JGM3	0.180	0.154	0.569	0.403
EGM96	0.217	0.287	0.509	0.651
EGM2008	**0.146**	**0.055**	**0.072**	**0.359**
EIGEN2	0.152	0.068	0.085	0.370
GL04C	**0.146**	**0.054**	**0.072**	**0.360**
GGM03S	**0.146**	**0.054**	**0.073**	**0.359**

Table 4. RMS(m) in the radial direction in 120 min prediction.

For the new generation of the gravity models, although the RMS in radial direction obtained by the 120-minute orbit prediction is very close, for a large part of the time points, the prediction effect of EIGEN2 is poor with the other three models (see Table 4). The further reason is that EIGEN2 only used half a year of CHAMP data, while all the other models used about four years of GRACE data. The accuracy of the gravity model obtained solely by the CHAMP satellite is weaker than that of the GRACE data obtained based on low tracking, and the CHAMP data used by EIGEN2 only covers half a year.

By further judging the gravity model of long-term orbit prediction by RMS in the radial direction, we found that the prediction situation of long-term orbit prediction is much more complex than that at 120 minutes prediction.

Within the data range, the gap between the new generation and the old generation does not increase with the prediction time, EIGEN2, JGM3 and EGM96, three models in the poor short term, exceed EGM2008、GGM03S、Gl04C in the prediction accuracy of some arcs in long-term prediction. (See Figure 3)

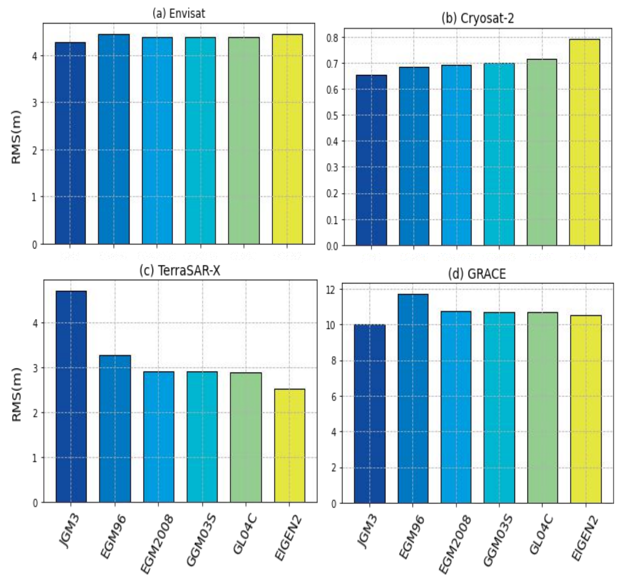

Figure 3. Comparison of 3-days different satellite orbits prediction precision with the different gravity models.

In this case, we believe that although the overall accuracy of EGM2008, GL04C and GGM03S are better than the other three models, JGM3, EG96 and EIGEN2 are highly sensitive to a part of the orbit, so in its sensitive part of the orbit, the prediction accuracy is high, and finally shows a trend of large fluctuations. In the long term, it affects the RMS results in the radial direction.

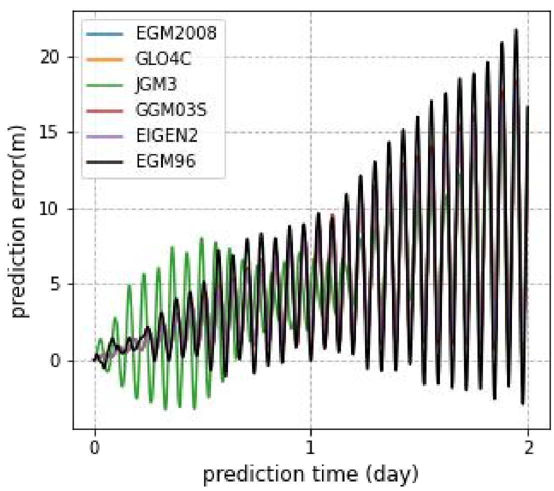

Figure 4. The GRACE satellite orbit prediction error (radial direction) in 1st Jan 2012.

3.3 Impact of Gravity Model Orders

We also compare the prediction effects at different orders of the same gravity field model. According to (F. Wang, Wang, Gong, & Xia, 2017), when the truncation error is at 0 ~ 10 nm/s², for 400 km orbit height, it requires 150 order, while the 1 400 km orbit height only needs 50 order to satisfy the model. In the process of orbit prediction, We also find the effect of the satellite orbit altitude on the order of the gravitational field.

In the interval from January 1 to January 4, 2011,4500 minutes. Six models were selected with order 10 as the truncation interval. The prediction result is shown in Figure 3.

The orbital altitude of the three satellites is about 480km, 710km and 970km, respectively. It can be seen that for satellites with different orbital altitude, the truncation order required to achieve a certain accuracy under the same prediction time and the prediction time required to achieve the insignificant order change are different.

For satellites with lower orbital altitude, the gravity perturbation is more obvious, and the gravitational field order required to achieve a certain truncation error is higher than for satellites with higher orbital altitude. Taking the 30-minute orbit prediction as an example, in order to reach a truncation error of 0.2m RMS in the radial direction, satellites with an orbital height of 480km need a truncation order of order 50, while under the same conditions, satellites with an orbital height of above 710km need only order 30 to achieve the same error. To achieve a cutoff error of 0.1m, a 710km satellite needs 40 orders, while a 970km satellite only needs about 30 orders to achieve this prediction effect.

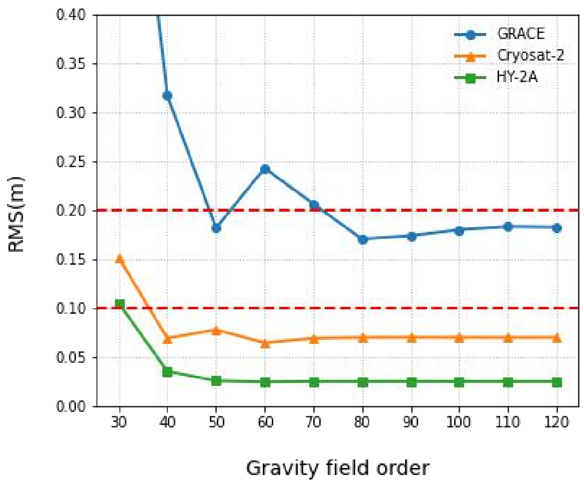

Figure 5. RMS(m) in radial direction for different orders in 30 minutes prediction.

We can also see the influence of orbital height on the order of gravity field with the prediction time. The orbital prediction time increases, other perturbation errors increase cumulatively, the error impact caused by the gravitational field truncation is getting smaller and smaller, and the effect of improving the truncation is less and less obvious. However, for the satellites with low orbit altitude, because the impact of gravity field is more influential on the satellites with low orbit, it is much longer for the satellites with lower orbit to achieve the unobvious truncation increase under the same order.

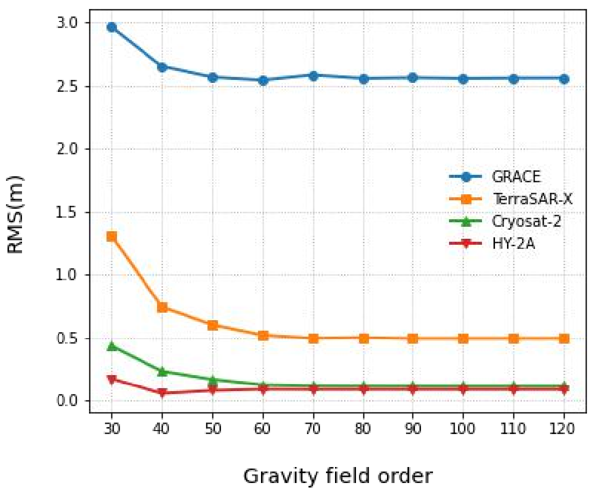

Figure 6. LEO Orbit Prediction Error in the radial direction of different satellites for different orders for 1-day prediction.

The authors use the 0.05 m RMS as an indicator of the unnoticeable change. For satellites higher than 480 km, 1 day of orbit prediction time, there is still a 0.08 m between orders 40 and 50, and the change is not obvious above order 50. For the 710 km orbit satellite, 30 minutes of orbit prediction time, 40 orders above the change has been not obvious. Further looking at the orbital altitude of 960 km, the change above 40 is not obvious in 30 minutes prediction, the change above 30 is not obvious in 2 hours prediction(the difference between 30 and 40 is less than 0.05 m RMS).

3.4 Impact of Permanent Tide

The authors calculate the prediction error to compare before and after correction of zero-tide models JGM3 and GGM03S for different satellite orbits. The results show that the permanent tidal modification has some effect on the orbit, and this effect is closely related to the orbital altitude and prediction time. The authors subtract the orbit accuracy performed before and after the correction to illustrate the effect of this correction on the orbit prediction (See Figure 7). In 1 day, for satellites with an orbital altitude of about 970km, the effect of permanent tides on 3D RMS is 6.92m; for satellites around 710km, the effect of permanent tides on 3D RMS is 4.20m; for satellites around 970km, the effect of permanent tides on 3D RMS is 2.07 m.

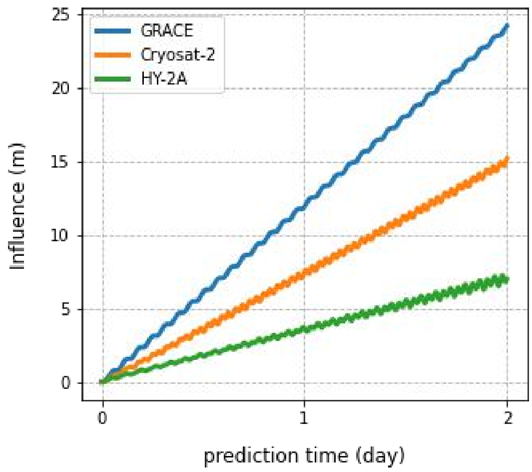

Figure 7. The influence of permanent tide on 3D prediction error of different satellites.

4. CONCLUSION

This paper introduces the influence of the gravitational field on the prediction of the orbit and compares the different gravitational field models. In contrast, not only the length of the prediction time but also the gravitational field order, the orbital altitude and other aspects have been considered. Further, the effect of permanent tidal on the orbit prediction is highlighted.

From different prediction comparison results, we obtained the following conclusions and suggestions:

(1) For the short time prediction, EGM2008, GL04C and GGM03S models have obvious advantages. In order to ensure high accuracy, these three models should be used.

(2) The accuracy of atmospheric modeling also affects the evaluation of gravity accuracy in orbit prediction. In order to ensure that the high precision gravity model can obtain a better prediction accuracy, for other models (e. g. atmospheric), high precise corrections are needed.

(3) EGM96, JGM3, EIGEN2 are suggested for the long-term prediction. Before prediction, the orbit can test three models to achieve good prediction accuracy.

(4) In the orbit prediction, the gravity model order required for satellites of different orbit altitudes to achieve a certain truncation error is different. For satellites with an orbit altitude of about 480km, the prediction needs to maintain a truncation above order 50 within 1 day. For satellites with an orbit altitude of about 710km, a truncation above order 40 should be maintained in the short term, and only a truncation of about order 30 should be maintained in the long term.

(5)The C20 permanent tidal correction can impact the prediction accuracy, the C20-term correction is necessary for the zero-tide-model before the tidal correction, and the C20 correction for the zero-tide and tide-free-model comparison should also be made before comparison.

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REFERENCES

Guo, J., Qin, J., Kong, Q., & Li, G. (2012). On simulation of precise orbit determination of HY-2 with centimeter precision based on satellite-borne GPS technique. Applied Geophysics, 9(HY2A gravity comparaision), 95-107. doi:10.1007/s11770-012-0319-3

Guo, X., Wang, L., Fu, W., Suo, Y., Chen, R., & Sun, H. (2021). An optimal design of the broadcast ephemeris for LEO navigation augmentation systems. *Geo-spatial Information Science*. doi:10.1080/10095020.2021.2017760

Pavlis, N. K., Holmes, S. A., Kenyon, S. C., & Factor, J. K. (2012). The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research: Solid Earth, 117*(B4), n/a-n/a. doi:10.1029/2011jb008916

Poutanen, M., Vermeer, M., & Maikinen, a. J. (1996). The permanent tide in GPS positioning. *Journal of Geodesy, 70*, 499–504. doi:10.1007/BF00863622

Sośnica, K., Thaller, D., Jäggi, A., Dach, R., & Beutler, G. (2012). Sensitivity of Lageos Orbits to Global Gravity Field Models. *Artificial Satellites, 47*(2), 47-65. doi:10.2478/v10018-012-0013-y

Tapley, B. D., Watkins, M. M., Ries, J. C., Davis, G. W., Eanes, R. J., Poole, S. R., . . . Williamson, R. G. (1996). The Joint Gravity Model 3. *Journal of Geophysical Research: Solid Earth, 101*(B12), 28029-28049. doi:10.1029/96jb01645

Wang, F. (2006). *Theory and Software Development on Autonomous Orbit Determination with Spaceborne GPS Measurements.* (Doctor), Wuhan University, Available from Cnki

Wang, F., Wang, J., Gong, X., & Xia, B. (2017). A Method to Determine the Optimal Degree and Order for the Earth Gravity Model in Real-Time Orbit Determination,Using Space-Borne GPS Measurements. *Journal of Geodesy and Geodynamics, 37*(02), 149-153. doi:10.14075/j.jgg.2017.02.009

Wang, H., Zhao, C., Zhang, W., Zhan, j., & Yu, S. (2016). Evaluation of Gravitational Field Models Based on the Laser Range Observation of Low Earth Orbit Satellites. *Chinese Astronomy and Astrophysics, 40*(3), 386-398. doi:10.1016/j.chinastron.2016.07.008

Wang, L., Li, D., Chen, R., Fu, W., Shen, X., & Jiang, H. (2020). Low Earth Orbiter (LEO) Navigation Augmentation: Opportunities and Challenges. *Strategic Study of CAE, 22.* doi:10.15302/J-SSCAE-2020.02.018

Wang, Z., & Zhang, B. (2016). Impact of Gravity Field Model on Reduced-dynamic Orbit Determination for Swarm Satellites. *GEOSPATIAL INFORMATION, 14*(11), 1-3. Retrieved from https://kns.cnki.net/kcms/detail/42.1692.P.20161115.1455.002.html.