Near Real-Time Global Density Estimation Using Satellite Precision Orbit Ephemerides

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Precise orbit determination and orbit prediction are vital to scientific satellite mission and mission operation. A predominate source of dynamical model uncertainty for low Earth-orbiting (LEO) spacecraft is incapable of properly modelling all of the density variations in the Earth's upper atmosphere. In order to solve the problem of modelling atmospheric density for satellite drag, this paper uses the near-time precision orbit ephemerides (POE) to calibrate the atmospheric density, such as Champ, Grace-A/B, COSMIC, TerraSAR-X, ICESat. Jacchia 1971, Jacchia-Roberts, CIRA 1972, and NRLMSISE 2000 are used as baseline density models, and atmospheric density and ballistic coefficient are estimated simultaneously using a sequential filter, the square root information filter (SRIF). We implements the density estimation capability into the newly developed EPOS-RT (Earth Parameter and Orbit determination System in Real-Time) software package which is designed and developed recently at GFZ for real-time applications. The effect of different Gauss-Markov exponential half-life values in orbit determination to estimate atmospheric density is investigated. The POE of Grace-A/B derived densities are evaluated by comparing them with accelerometer derived densities.

I. INTRODUCTION

Most sources of error in orbit propagation and orbit determination, including a non-spherical earth, third-body effects, solar radiation pressure, and tides, have been modeled with fair precision. However, measurements of extreme upper atmospheric density have shown that current models fail to model the variability in this region, such as Jacchia-Roberts or MSISE-90 can only approach 10% accuracy in quiet conditions and 20%-30% in high solar activity. Satellite orbits passing through the thermosphere and exosphere rely on these models, and consequently, orbit determination and prediction is subject to weaknesses in these models. Improved knowledge of upper atmospheric density will allow for improved orbit determination, which will help prevent collisions, as well as improve prediction of satellite life-spans. There are several methods of modeling atmospheric density for satellite drag analysis. Dynamic calibration of the atmosphere (DCA) is a method by which density values obtained from existing atmospheric models are improved or corrected, and the other is the use of onboard accelerometers which measure non-conservative accelerations such as drag.

Cefola [1] used TLE data to creat corrections to Russian GOST model, which are made for a one day grid using the TLE data as well as solar and geomagnetic activity data as inputs with hundreds of satellites in LEO are examined from April 2002 to January 2003. Storz [2] utilized 75 inactive payloads and debris to solve for a global correction to density that changes dynamically in the thermosphere and exosphere every three hours, which is called the High Accuracy Satellite Drag Model (HASDM). Recent research using DCA has been performed using GEODYN, the NASA Goddard Space Flight Center Precision Orbit Determination and Geodetic Parameter Estimation Program [3]. Doornbos [4] used TLE data to calibrate the neutral density of the thermosphere, and improvements were made in error from around 30% for the base models to around 15% using a single daily parameter.

Bruinsma and Biancale [5] first derived density from CHAMP accelerometer data, and Schlegel used [6] the CHAMP accelerometer to characterize thermospheric density structures in polar regions. Collaboration between the Centre National d'Études Spatiales (CNES) and the University of Colorado researchers produced several publications using accelerometer data from CHAMP and GRACE [7][8][9][10][11][12]. Bruinsma and Forbes [13] further examined the use of the STAR accelerometer aboard CHAMP to identify density variability.

However, DCA also models the atmosphere discretely based on the intervals of input data. This results in continuous solutions over these intervals, but causes discontinuities between intervals. Finally, the use of TLE data by most DCA schemes limits the accuracy of the results. And, these approaches are limited temporally by the use of daily solar flux or averaged geomagnetic indices. A weakness of the accelerometer density method is the low number of spacecraft and limited altitude ranges and spatial coverage. DCA on the other hand, possesses many satellites and a great deal of data but is not nearly as accurate.

James R. Wright [14], Eric Dale Fattig [15], and Andrew Timothy Hiatt [16] demonstrated the simultaneous real-time estimation of both atmospheric density and ballistic coefficient with simulated range data and with real range data. The approach tested is valid when the exponential half-life on ballistic coefficient errors is significantly different than that on atmospheric density errors.

This paper firstly introduces the research strategy briefly including processing strategies, data, and results analysis. Then, based on the strategy various scenarios are selected as experiments by EPOS-RT for simultaneous real-time estimation of both atmospheric density and ballistic coefficient. Finally, the results of experiments are analyzed in detailed before the conclusions are drawn.

II. RESEARCH STRATEGY

Orbital drag acceleration (a_D) for a satellite in the Earth's atmosphere is expressed in the following form:

$$a_D = -\frac{1}{2}\frac{C_D A}{M}\rho V^2 \tag{1}$$

Where ρ is the atmospheric density and C_D, A, M and V are satellite's drag coefficient, area, mass and velocity relative to the ambient gas.

The estimation errors Δa_D in LEO air-drag accelerations a_D are due most significantly to random errors in modelled atmospheric density ρ and ballistic coefficient B, $B = C_D A/M$. Differentiation of Eq. 1 provides:

$$\Delta a_D = (\frac{\Delta B}{B} + \frac{\Delta\rho}{\rho})a_D \tag{2}$$

The baseline atmospheric model chosen generates a density, ρ. Corrections to the density, Δρ/ρ, and corrections to the ballistic coefficient, ΔB/B, are generated from the estimation process. Given x = x(t) is a dynamic scalar random variable, which in this case is either density or ballistic coefficient, the following equation is satisfied for an exponential Gauss-Markov sequence:

$$x(t_{k+1}) = \Phi(t_k, t_{k+1})x(t_k) + \sqrt{1-\Phi^2(t_{k+1}, t_k)}w(t_k) \tag{3}$$

In this equation, w (t) is a Gaussian variable possessing zero mean and constant standard deviation. This white noise function is also dependent only on the previous measurement, and thus is a Markovian process as well. The initial value of the Gaussian white noise variable is equal to the initial value of the dynamic scalar random variable. The following equations define the transition function:

$$\Phi(t_k, t_{k+1}) = e^{\alpha|t_{k+1}-t_k|}$$

$$\alpha = \ln(1/2)/\tau \tag{4}$$

The half-life, τ, is the half-life input by the user.

All the experiments are carried out with EPOS-RT [17] that is designed and developed recently at GFZ for real-time applications with the capability of integrated adjustment with GNSS data, accelerometer data, K-band range and range-rate data, and ground-based SLR data.

For results analysis, we compare the POE derived densities to accelerometer derived densities with cross correlation coefficient, which is a non-dimensional number which can be between -1 to +1 and is to quantify how two signals correlate. A value of 1 indicates that there is perfect correlation between the two; a value of -1 indicates that the signals correlate in an inverse manner, and a value of zero indicates that there is no correlation between the two.

Consider two signals or datasets, $x(i)$ and $y(i)$, where i=0, 1, 2, …., N is the number of elements in each dataset. Then, the zero delay cross correlation is given by the following expression:

$$CC = \frac{\sum_{i=1}^{N}\left[(x(i)-\bar{x})(y(i)-\bar{y})\right]}{\sqrt{\sum_{i=1}^{N}(x(i)-\bar{x})^2}\sqrt{\sum_{i=1}^{N}(y(i)-\bar{y})^2}} \tag{5}$$

Where, $\bar{x}$ and $\bar{y}$ are the mean values of the datasets $x(i)$ and $y(i)$, respectively.

III. EXPERIMENTS AND SIMULATION STUDY

In this paper, the data to be adjusted simultaneously is GRACE-A POE on DOY 001 in 2010, GRACE-B POE on day 001 in 2008, and accelerometer derived densities from Version 2.2 densities [18]. Multiple atmospheric models are examined, including Jacchia 1971 [19], Jacchia-Roberts [20], the Committee on Space Research (COSPAR) International Reference Atmosphere, CIRA 1972 [21], and the Naval Research Laboratory MSISE model (NRLMSISE 2000) [22].

The precision orbit ephemerides (POE) are used as measurement data to generate corrections to density values obtained from existing atmospheric models. Tab. 1 summaries the satellite force models and the surface properties are listed in Tab. 2 for computing the solar radiation pressure in the Satellite Frame [23].

The nominal ballistic coefficient of GRACE is 0.00687 m^2/kg [15], and the results as shown in the Tab. 3 and Fig. 1~5.

Table 1 The satellite force models

Satellite force models	Description
Mean earth gravity	EGM96 120×120
N-body	DE 405 (SUN MOON MERC VENU MARS JUPI SATU)
Solid earth tide	IERS 2003
Ocean tide	CSR 4.0
Solar radiation	Computed for all panels
Relativity	IERS 2003
Atmospheric drag	DTM94
Empirical force	2 parameters in each ACR directions
Integrator	Step: 5 s, Adams order: 7
Atmospheric density half-life	180 min [15]
Ballistic coefficient half-life	1.8 min [15]

Table 2 The surface properties of GRACE

Panel	Area(m2)	Unit Normal X	Y	Z	Emiss	Absorp
Front	0.9551567	+1.0	0.0	0.0	0.62	0.34
Rear	0.9551567	-1.0	0.0	0.0	0.62	0.34
Starboard (outer)	3.1554792	0.0	+0.766044	-0.642787	0.81	0.65
Starboard (inner)	0.2282913	0.0	-0.766044	+0.642787	0.62	0.34
Port (outer)	3.1554792	0.0	-0.766044	-0.642787	0.81	0.65
Port (inner)	0.2282913	0.0	+0.766044	+0.642787	0.62	0.34
Nadir	6.0711120	0.0	0.0	+1.0	0.75	0.12
Zenith	2.1673620	0.0	0.0	-1.0	0.81	0.65
Boom	0.0461901	——	——	——	0.62	0.34

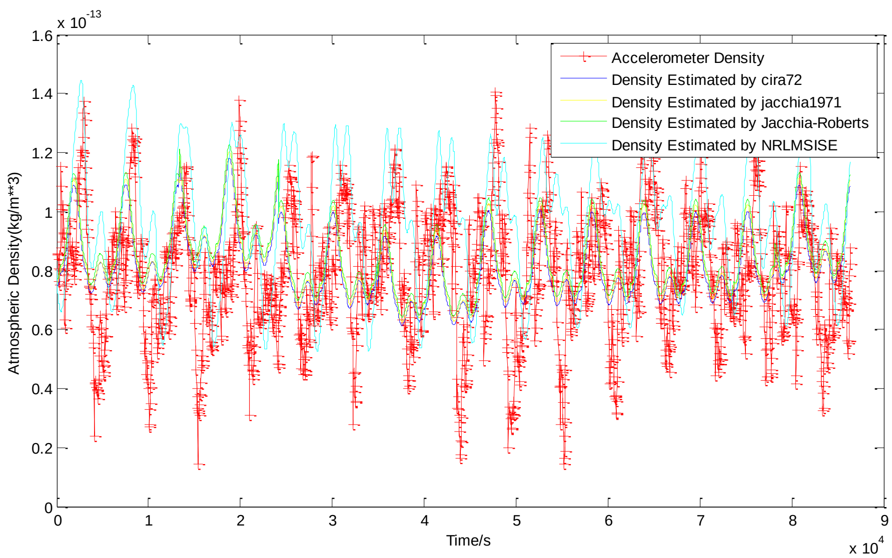

Figure 1 POE Estimated Density Based on Jacchia 1971, Jacchia-Roberts, CIRA 1972, NRLMSISE 2000 Model Density and Accelerometer Density of GRACE-B Satellites for Jan. 1, 2008.

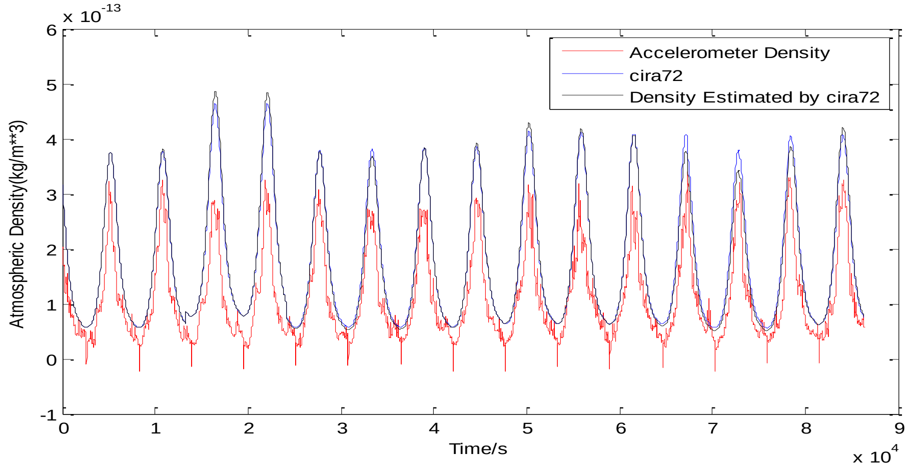

Figure 2 POE Estimated Density Based on CIRA 1972, CIRA 1972 Model Density and Accelerometer Density of GRACE-A Satellites for Jan. 1, 2010.

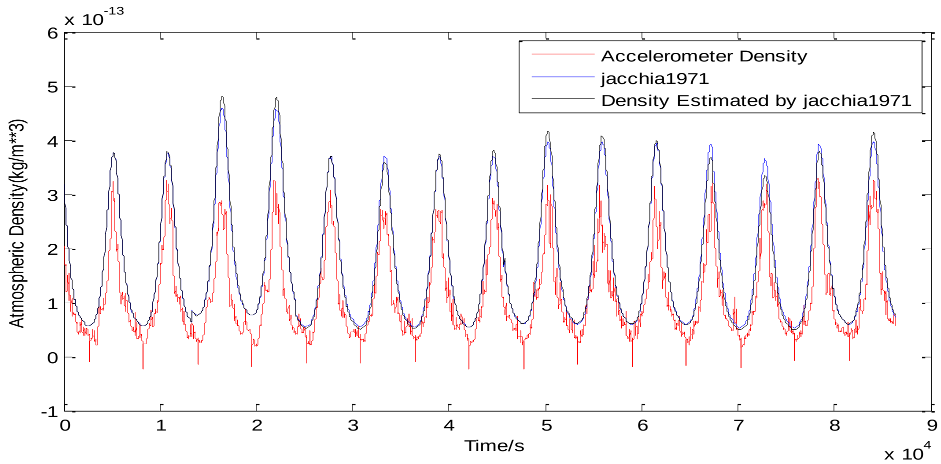

Figure 3 POE Estimated Density Based on Jacchia 1971, Jacchia 1971 Model Density and Accelerometer Density of GRACE-A Satellites for Jan. 1, 2010.

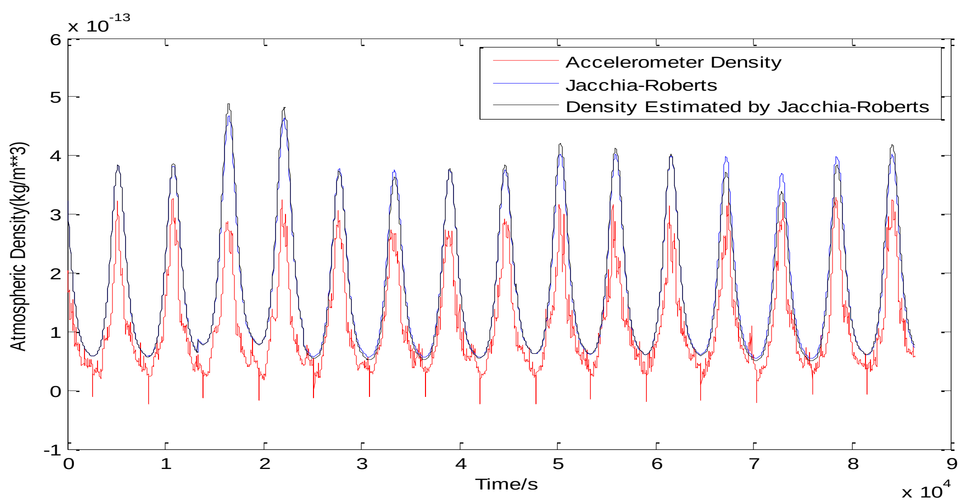

Figure 4 POE Estimated Density Based on Jacchia-Roberts, Jacchia-Roberts Model Density and Accelerometer Density of GRACE-A Satellites for Jan. 1, 2010.

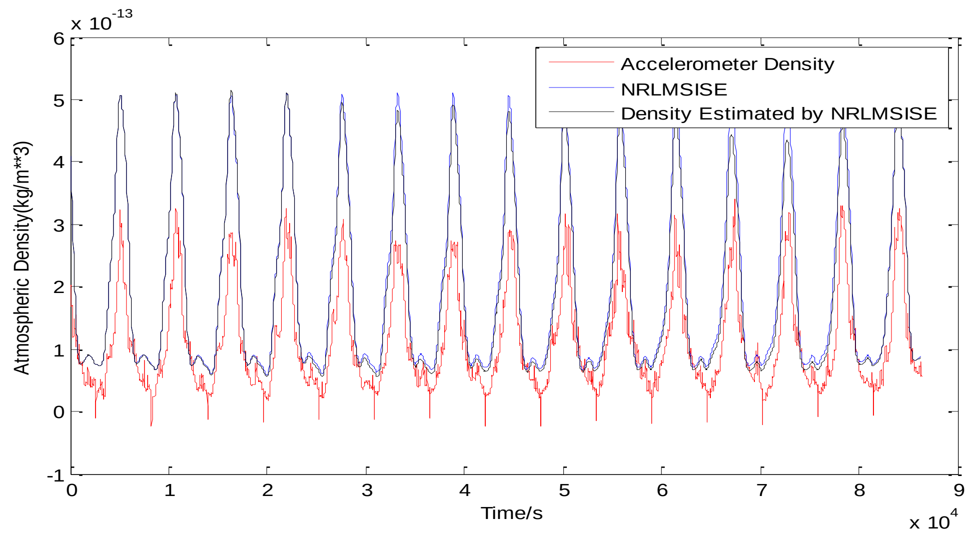

Figure 5 POE Estimated Density Based on NRLMSISE 2000, NRLMSISE 2000 Model Density and Accelerometer Density of GRACE-A Satellites for Jan. 1, 2010.

Table 3 Zero Delay Cross Correlation Coefficients for GRACE.

		Cira72	Jacchia 1971	Jacchia-Roberts	NRLMSISE 2000
GRACE-A	Model	0.9488	0.9482	0.9483	0.9604
	Estimated	0.9576	0.9566	0.9568	0.9618
GRACE-B	Model	0.8011	0.8014	0.8010	0.8094
	Estimated	0.8189	0.8214	0.8188	0.8282

IV. CONCLUSION

First the POE estimated densities are superior to model density in comparison with accelerometer density. Secondly, the CIRA-1972, Jacchia 1971, Jacchia-Roberts, and NRLMSISE 2000 based POE density estimates all have very similar results with very slight differences between them. The preliminary research shows that the processing stragies is feasible and build up a good basis for simultaneous real-time estimation of both atmospheric density and ballistic coefficient. However, there are many jobs to do in the future, including specifying the ballistic coefficient correlated half-life and density correlated half-life, investigating the effect of solar activity and geomagnetic activity on atmospheric density estimates, and considering the sensitivity of the density estimates to the initial ballistic coefficient.

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