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Analysis of Atmospheric Drag Acceleration and Engineering Realization of Space Target

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***Abstract*—Space target orbit determination module is an important component of space target surveillance radar system. The development of this module requires very complex aerospace dynamics knowledge, which brings great difficulties to non-orbit mechanics researchers engaged in radar system design. The core of orbit determination is the calculation of perturbation acceleration, which is the basis of high precision numerical orbit calculation. To this end, this paper takes the atmospheric drag perturbation which can not be ignored in the precise orbit determination of LEO satellite as an example, introduces its mathematical principle, gives the program design idea and function interface implementation, and makes a simulation comparison with STK. The experimental results verify the effectiveness of the interface function, and show that the function interface designed in this paper can assist researchers in radar system design.**

Keywords-space target; atmospheric drag; acceleration; orbit determination

I. Introduction

Space target orbit determination module is an important component of space target surveillance radar system. The development of this module requires very complex aerospace dynamics knowledge, which brings great difficulties to non-orbit mechanics researchers engaged in radar system design. Although there are some open source orbit determination softwares for references [1-5], these softwares are mainly used to process optical observation data and are not suitable for processing radar observation data. To this end, the author developed the RadarOrbDet library [6] to assist non-orbital mechanics personnel in the system design of space target surveillance radars. The coordinate conversion module [7] and the initial orbit determination module [8] have been developed. This article studies the development of the orbit improvement module.

Orbit improvement is the key and difficult point in determining the orbit of a space target. It involves a lot of content, including perturbation analysis, variational analysis of partial differential equations, least squares optimization and other theories [9]. This article focuses on perturbation analysis, which is the basis for realizing high-precision orbit calculation. Its core is to analyse the force model of the target and calculate various perturbation accelerations. In addition to the central gravity of the earth, other small forces that the space targets orbiting the earth subjected to are collectively referred to as perturbations, including non-spherical perturbation of the earth, air-drag perturbation, sun-moon gravitational perturbation, etc. [9]. This paper studies the atmospheric drag perturbation, and introduces the analysis method of acceleration and its engineering realization, which is especially important for the precise orbit determination of medium and low orbit satellites.

The main content of this paper includes mathematical principles of the atmospheric drag perturbation acceleration, program design ideas and use of STK software to verify the effectiveness of the interface function.

II. Mathematical Principle of the Atmospheric Drag Perturbation Acceleration

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The dominant atmospheric force acting on low altitude satellites, called drag, is directed opposite to the velocity of the satellite motion with respect to the atmospheric flux, hence decelerating the satellite. The relationship between the drag and the velocity $\boldsymbol{v}_\mathrm{r}$ of the satellite relative to the atmosphere is deduced as follows [10].

Consider a small mass element Δm of an atmosphere column that hits the satellite's cross-sectional area A in some time interval Δt

$$\Delta m = \rho A v_\mathrm{r} \Delta t \tag{1}$$

where ρ is the atmospheric density at the location of the satellite. The impulse dp exerted on the satellite is then given by

$$\Delta p = \Delta m v_\mathrm{r} = \rho A v_\mathrm{r}^2 \Delta t \tag{2}$$

Using $F=\Delta p/\Delta t$, the satellite acceleration due to drag can therefore be written as

$$\ddot{\boldsymbol{r}} = -\frac{1}{2} C_D \frac{A}{m} \rho v_\mathrm{r}^2 \boldsymbol{e}_v \tag{3}$$

where m is the spacecraft mass. The drag coefficient C_D is a dimensionless quantity that describes the interaction of the atmosphere with the satellite's surface material. Typical values of C_D range from 1.5-3.0, and are commonly estimated as free parameters in orbit determination programs. A crude approximation is C_D=2 in the case of a spherical body, whereas typical values for non-spherical convex-shaped spacecraft range from 2.0 to 2.3. The direction of the

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drag acceleration is always (anti-)parallel to the relative velocity vector as indicated by the unit vector $\boldsymbol{e}_v=\boldsymbol{v}_r/v_r$. Here the factor of 1/2 has been introduced to preserve a consistent notation in all branches of aerodynamics.

The area-to-mass ratio in principle requires the knowledge of the spacecraft attitude. A constant area-to-mass ratio can, however, be assumed in the Earth-pointing mode, where one of the satellite's main axes of inertia is permanently aligned with the radial direction vector.

The relative velocity of the satellite with respect to the atmosphere depends on the complex atmospheric dynamics. However, a reasonable approximation of the relative velocity is obtained with the assumption that the atmosphere co-rotates with the Earth. Therefore one can write

$$\boldsymbol{v}_{\mathrm{r}} = \boldsymbol{v} - \boldsymbol{\omega}_{\oplus} \times \boldsymbol{r} \tag{4}$$

with the inertial satellite velocity vector $\boldsymbol{v}$, the position vector $\boldsymbol{r}$, and the Earth's angular velocity vector $\boldsymbol{\omega}_{\oplus}$ of size 0.7292×10^{-4} rad/s.

III. Brief Introduction of Atmospheric Model

The drag depends on the atmospheric density ρ at the location of the satellite, and the atmospheric density is usually calculated by the semi-empirical atmospheric density model. At present, the commonly used atmospheric models in orbit determination include CIRA (COSPAR International Reference Atmosphere), Jacchia, DTM and MSIS.The CIRA series recommended by the COSPAR Committee on Space Research include CIRA1961, CIRA1965, CIRA1972 and CIRA1986.The Jacchia series, based on atmospheric density data retrieved from satellite orbital decay data, include J65, J70, J71, J77, MSFC/J70, MET and MET V2.0. The DTM series include DTM78, DTM94, and DTM2000. In the high thermosphere, the MSIS series models fit the measurement data of satellite, mass-spectrometer data, and ground incoherent scatter radar, etc., and in the low thermosphere they are close to the the global general circulation model [11].

The Jacchia-70 model is a general atmospheric model for LEO orbit determination and prediction program, but its prediction accuracy cannot meet the practical application requirements. At present, NRLMSISE-00(US Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Extend) atmospheric model is mostly used. It plays an important role in orbit determination and prediction of spacecraft.

The NRLMSISE-00 atmospheric model was developed on the basis of the MSISE-90 model in 2000. MSIS stands for Mass Spectrometer and Incoherent Scattering Radar, and E means the model covers from the ground to the bottom of escaping layer, while earlier models only covered the thermosphere. This model has 8 input items: The number of days from January 1 of current year to current day, the number of seconds from 00:00:00 to the calculating time, geographical longitude, latitude, altitude, the solar radiation flux of 10.7cm on previous day ($F_{10.7}$), The average $F_{10.7}$ for 81 days (3 solar rotation cycles, with the current day as the midpoint), average geomagnetic index (Ap) of current day and the twenty 3h average values of Ap before the calculating time. The outputs include the number densities of N_2, O_2, He, Ar, N, H, O and O+, the neutral atmospheric temperature and the atmospheric density.

The early $F_{10.7}$ was mainly produced by the Atmosphere Explorer (AE) satellites and the mass- spectrometer and solar EUV absorption measurement devices on the rocket. The NRLMSISE-00 model incorporates solar EUV absorption measurements from NASA's Solar Peak Year Program satellites. Ap is measured by geomagnetic stations around the world; Ground ISR radar stations are mainly used to monitor the ionosphere. These instruments are also used to monitor atmospheric temperature and the density of various gases.

These space environment parameters are provided by the file SpaceWeather.txt. Each line in the file represents a spatial environment parameter record for the specified date, as shown in Fig. 1. The meaning of parameters related to atmospheric drag calculation is shown in Tab. I [12].

TABLE I. Meaning of Space Environment Parameters.

Column	Name	Description
001-004	yyyy	year
006-007	mm	month
009-010	dd	day
048-050	Ap0	The Ap index in the UT time range 00:00-03:00.
052-054	Ap3	The Ap index in the UT time range 03:00-06:00
056-058	Ap6	The Ap index in the UT time range 06:00-09:00
060-062	Ap9	The Ap index in the UT time range 09:00-12:00
064-066	Ap12	The Ap index in the UT time range 12:00-15:00.
068-070	Ap15	The Ap index in the UT time range 15:00-18:00.
072-074	Ap18	The Ap index in the UT time range 18:00-21:00.
076-078	Ap21	The Ap index in the UT time range 21:00-24:00.
114-118	Obs $F_{10.7}$	$F_{10.7}$ of the previous day (observed).
126-130	Obs Lst81	$F_{10.7}$ arithmetic mean for the previous 81 days (observed).

IV. Program Design

Fig. 2 is a program flow chart for calculating the perturbation acceleration of atmospheric drag.

```
------------------------------------------------------------------------------------------------------------------------------
                                                                                             Adj      Adj   Adj   Obs   Obs   Obs
yyyy mm dd BSRN ND Kp Kp Kp Kp Kp Kp Kp Kp Sum Ap  Ap  Ap  Ap  Ap  Ap  Ap  Ap  Avg Cp C9 ISN F10.7 Q Ctr81 Lst81 F10.7 Ctr81 Lst81
------------------------------------------------------------------------------------------------------------------------------
yyyy mm dd nnnn nn nn nn nn nn nn nn nn nn nnn nnn nnn nnn nnn nnn nnn nnn nnn nnn n.n n nnn nnn.n n nnn.n nnn.n nnn.n nnn.n nnn.n
------------------------------------------------------------------------------------------------------------------------------
2000 01 01 2272  7 53 47 40 33 43 30 43 37 327  56  39  27  18  32  15  32  22  30 1.3 6  48 125.6 0 160.5 175.0 129.9 165.6 179.0
------------------------------------------------------------------------------------------------------------------------------
```

Figure 1. Parameter format of spatial environment parameter record.

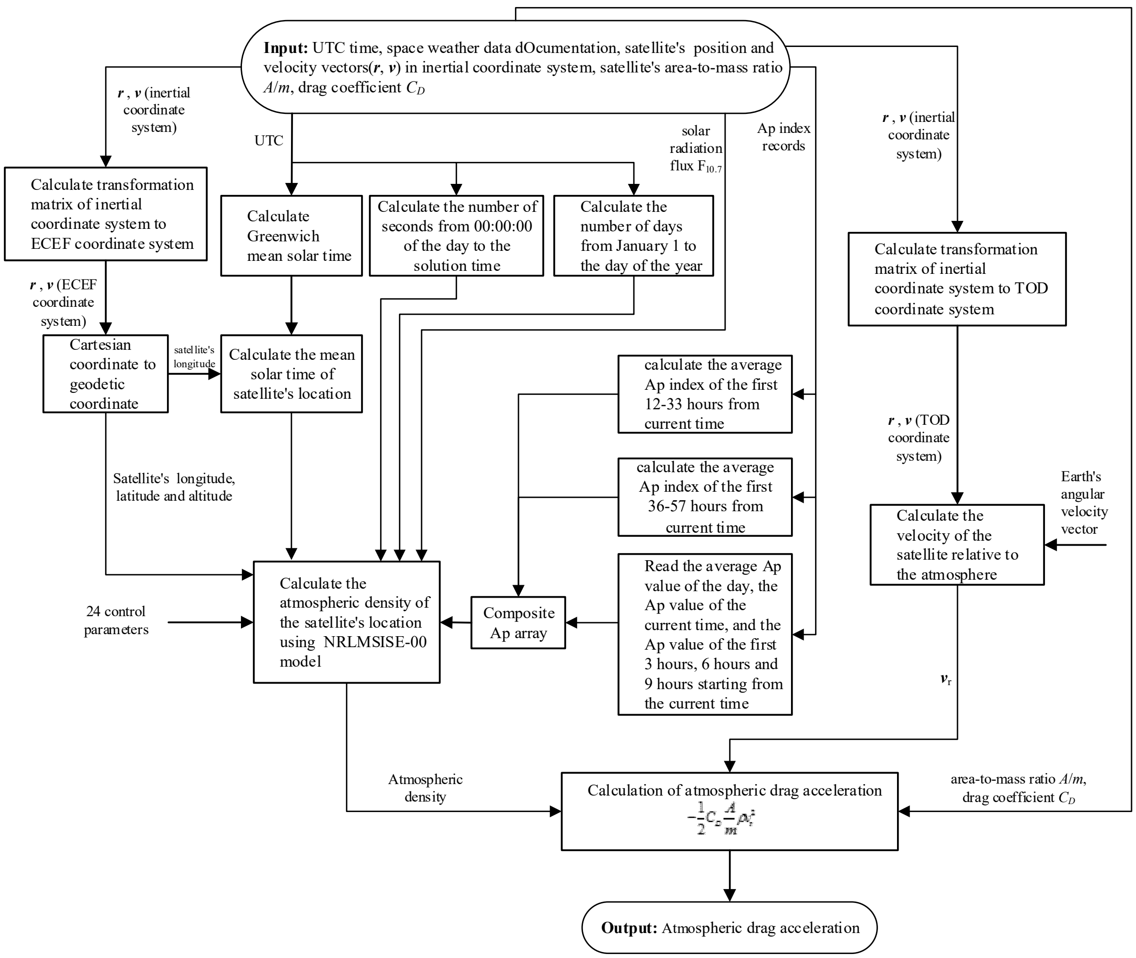

Figure 2. Program calculation flow chart for calculating the acceleration of atmospheric drag.

The main calculation process in Fig. 2 is as follows: the mean solar time, the number of seconds from 00:00:00 to the current time of the day, and the number of days from January 1 to the current day of the year are calculated using the input UTC time; the required Ap geomagnetic datum are obtained and calculted using the input space weather data document; the longitude and latitude of the satellite are calculated by the input satellite position vector. According to the above information, NRLMSISE-00 model is used to calculate the atmospheric density. Based on the position and velocity vectors of the satellite, the velocity of the satellite relative to the atmosphere is calculated according to the Earth's angular velocity vector. Finally, the atmospheric drag acceleration can be calculated from the relative velocity, atmospheric density, input area-to-mass ratio and drag coefficient.

V. SOFTWARE INTERFACE CALL AND VALIDITY VERIFICATION

A. Interface function description

According to the program design principle in part 4, the interface function for calculating the atmospheric drag perturbation acceleration is realized by using C language and integrated into radarbdet library [6]. The interface description of this function is shown in Fig. 3.

```
/*-----------------------------------------------------------------------------
*
*                         procedure rodAccelAirDragPerturbation
*
*  Calculate atmospheric drag acceleration
*
*  author        : Xiaobin Huang                  Feb 15, 2020
*
*  Input          Description                                              Unit
*    jd_utc       - Julian day of calculating time (UTC)
*    r_ei         - Satellite position vector (inertia coordinate system)    m
*    v_ei         - Satellite velocity vector (inertia coordinate system)    m/s
*    area         - sectional area of satellite                              m^2
*    mass         - mass of satellite                                        kg
*    cd           - drag coefficient (1.5~3.0, default 2.2)
*
*  output        :
*    a_ei         - atmospheric drag acceleration (inertia coordinate system)  m^2/s
*
------------------------------------------------------------------------------*/
void rodAccelAirDragPerturbation(double jd_utc, double r_ei[3], double v_ei[3],
    double area, double mass, double cd, double a_ei[3]);
```

Figure 3. Interface function description of atmospheric drag acceleration calculation.

B. *Interface function validity verification*

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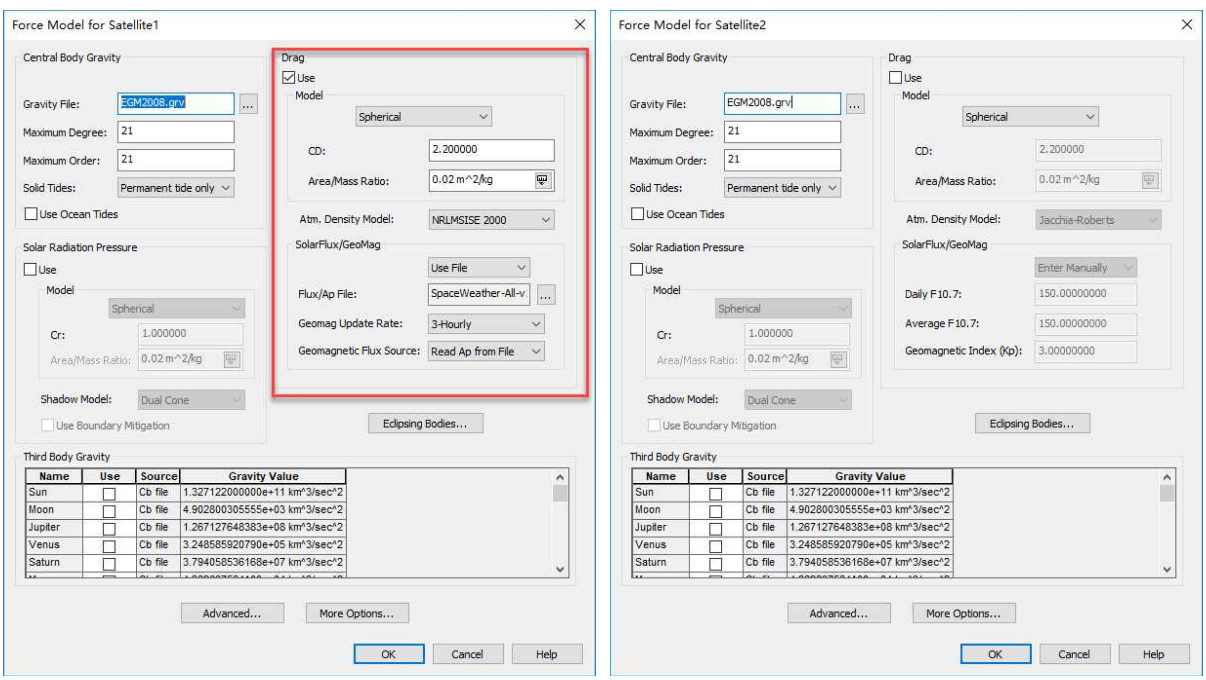
Two satellites are simulated in STK11.2, and their initial orbital elements are set to be the same, as shown in Tab. II. The first satellite is set with a 21st order gravity model pulse atmospheric drag perturbation. The second satellite is only set with a 21st order gravity model, as shown in Fig. 4. Using the report function of STK, the accelerations of the two satellites at 2016-06-16 04:00:00(STK11 does not contain the latest atmospheric model data, so use this time to ensure that our software and STK use the same atmospheric model data) are obtained respectively, and the atmospheric drag acceleration of the second satellite can be obtained by subtracting the two accelerations. In addition, another atmospheric drag acceleration can be calculated by calling the interface function shown in Fig. 4. These results are shown in Tab. III, using the relative error described in formula (5) for quantitative comparison.

$$\text{Relative error} = \frac{\left|\boldsymbol{a}_{\text{Software}} - \boldsymbol{a}_{\text{STK}}\right|}{\left|\boldsymbol{a}_{\text{STK}}\right|} \tag{5}$$

It can be seen from Tab. III that the error is 1.14%, indicating that the software algorithm in this paper is effective. The main error sources are the coordinate and time conversion, the truncation error of the calculation, etc.

TABLE II. SATELLITE ORBIT ELEMENTS.

Item	Value
Epoch	2016-06-16 04:00:00
Semi-major axis(km)	6678.14
Eccentricity	0
Inclination	28.5°
Argument of perigee	0°
Ascension of ascending node	0°
True anomaly	0°



(a) Satellite 1 (a) Satellite 2

Figure 4. Satellite force model setting.

TABLE III. COMPARISON OF ATMOSPHERIC DRAG ACCELERATION (STK AND OUR SOFTWARE).

Category	Item	Acceleration (m/s^2)		
		x	y	z
STK	Satellite 1	-8.9509556686	-1.123596×10^{-4}	-1.37593×10^{-5}
	Satellite 2	-8.9509556684	-1.037988×10^{-4}	-8.7521×10^{-6}
	Atmospheric drag perturbation	-2×10^{-10}	-8.5608×10^{-6}	-5.0072×10^{-6}
Software	Atmospheric drag perturbation	-6.6174×10^{-24}	-8.4633×10^{-6}	-4.9502×10^{-6}
Relative error		1.14%		

VI. CONCLUSION

This paper introduces the mathematical principle of atmospheric drag acceleration, describes the program design ideas and the interface function, and finally verifies the effectiveness of the algorithm with STK software. The analysis of least-squares orbit determination problem will be further studied in our next work.

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