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Stellar Sensor-based Automatic Satellite Navigation

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Abstract: This research project carried out a tentative study of automatic satellite navigation based on a stellar sensor. The study shows that with a known starlight refraction model of the Earth's atmosphere, automatic satellite navigation can be realized through starlight refraction measurement or obscuration time measurement, without the necessity of an accurate attitude determination. In the study report, a basic related navigation algorithm was proposed, the effect of errors was discussed, and several characteristics of such navigation were revealed through mathematic simulation calculations.
Key Words: Satellite, Automatic Navigation, Stellar Sensor

1. Introduction

To determine a satellite's orbit around the Earth with an automatic navigation system, the observation values must include those which can reflect the geometric relations between the satellite and the Earth. In automatic satellite orbit determination with a stellar sensor, there are three observation patterns, namely: (1) the included angle between the starlight and the geocentric direction; (2) the starlight refraction and (3) the Earth obscuration time.

Covered by the atmosphere, the horizon becomes more and more obscure as its brightness diminishes with altitude. With such a scenario, it is extremely difficult to accurately locate the horizon, which can lead to relatively low accuracy of the observation data concerning the geocentric direction obtained with an optical system.

If two stars are observed simultaneously with an in-satellite stellar sensor, in which the starlight of one star is at a much higher altitude than the atmosphere and therefore is not refracted, while the starlight of the other star, transmitting through the atmosphere, is subject to atmospheric refraction, then the angular distance between the two stars will differ from the nominal value. This change in value of the angular distance is referred to as the starlight refraction angle. Since there are fairly accurate data concerning the relationship between the starlight refraction angle and the atmospheric density, along with an accurate model reflecting the variation of atmospheric density with altitude, the altitude of the starlight in the atmosphere can thereby be determined more accurately. The observation value of this altitude can reflect the geometric relationship between the satellite and the Earth. Thus, the starlight refraction observation method, based on the atmospheric model, can provide relatively accurate observation data.

The degree of accuracy of the starlight refraction observation data relies on the precision of the atmospheric model within the entire range of the refraction altitude. It is obvious that the precision of the atmospheric model is more difficult to master in a wide range than at a designated altitude. In this case, another observation value can be selected which is associated with the starlight refraction at the designated altitude alone. This altitude can be defined as a designated horizon. Observation of the star rise and setting time at that horizonal plane can provide even more accurate information about the satellite location.

The atmospheric model varies with seasons and may cause a systematic error in the observation model leading to a large error in orbit determination. This systematic error is not observable in the case of automatic satellite navigation. Therefore, the automatic navigation system still needs assistance from the ground. The Earth-based station can conduct, within a short time, high precision and real time observations of the satellite location and with these data, can estimate the systematic error derived from the observation model during automatic navigation and correct the model. This paper presents a tentative discussion of this problem.

2. Orbit Model

The satellite orbit dynamic equation can be written as follows:

$$\ddot{r} = -\mu \frac{r}{r^3} + A(r, t) \qquad (1)$$

where r is the vector from the Earth's center to the satellite; A is perturbation acceleration.

The major problem in determining an orbit model is the selection of the perturbation value that affects the orbit. Numerically, the highest perturbation value is the earth figure perturbation, followed by the effect of air resistance and then, by the solar and lunar gravity perturbation.

The earth figure perturbation, though appearing to have the strongest effect, is a law which remains unchanged almost constantly and does not show much randomness. In addition, its effect on the orbit has been studied in detail in different ways. And it is believed that the orbit model is accurate enough in navigation research. In this paper, the earth figure perturbation is discussed by using the spherical harmonic function of the Earth's external gravity potential.

The atmospheric resistance can be described as follows:

$$A_d = -C_d |V| V \tag{2}$$

Since the atmospheric resistance shows fairly high randomness due to the uncertainty caused by the atmospheric fluctuation, the area of the aircraft front projection, resistance coefficient and other parameters, C_d is regarded as a constant to be estimated in this paper.

3. Starlight Angular Distance Observation Model

By using an optical system, the geometric relationship between the satellite and the Earth--the satellite vertical direction or the tangential direction of the satellite and the horizon--can be directly measured, on the basis of which the direction of the line connecting the satellite and the geocenter (briefly the geocentric direction) in the satellite intrinsic coordinate E can be calculated. Similarly, with the stellar sensor, the direction of a known star in the satellite intrinsic coordinate S, and further the included angle between the two directions α_s, referred to as the starlight angular distance, can also be calculated as shown in Fig. 1.

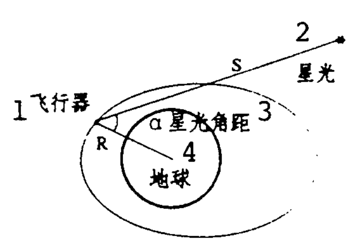

Fig. 1. Starlight Angular Distance Observation
Key: (1) Aircraft; (2) Starlight; (3) Starlight angular distance; (4) Earth

The starlight angular distance is the included angle between two vectors at a particular time, whose degree is not related to any specific coordinate system, while the intrinsic coordinate serves as the most convenient reference for calculations. The measurement error of the starlight angular distance is the sum of the measurement errors of the geocentric direction and starlight direction, with the former being the major source of errors.

The geocentric direction vector and starlight vector can also be used in attitude determination but the starlight angular distance cannot.

The included angle of the starlight angular distance in different coordinate systems remains unchanged, and the angular distance α_s measured in the intrinsic coordinate is also applicable to the inertial coordinate. Therefore, the observation model which is designed to conduct a state estimation of the satellite location vector can be expressed directly in the inertial coordinate as:

$$\alpha_S = \arccos\left(\frac{\boldsymbol{r} \cdot \boldsymbol{S}}{|r|}\right) + \alpha_b \tag{3}$$

where α_b is the systematic error observed.

4. Starlight Refraction Observation Model

The atmosphere refracts the starlight inward with its refraction angle ever increasing as the incident light approaches the Earth's surface. In this case, the star is still visible while located under the star horizon plane as seen in Fig. 2. The starlight rises from the horizon at an earlier time at the head of the satellite (along the velocity direction) and at a later time at the tail of the satellite (counter velocity direction).

The filtering equation involves the partial derivative matrix of the measured values with respect to the state value. To avoid calculating odd points, the refraction angle should be converted, by using the atmospheric refraction model, into the starlight tangential height before being filtered.

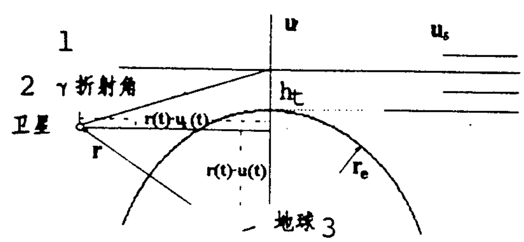

Fig. 2 Starlight Refraction Observation

Key: (1) Refraction angle; (2) Satellite; (3) Earth

The atmospheric refraction model may introduce observation errors, yet in the proper way, the functional relation between the refraction angle and the starlight tangential height can be accurately approximated through using the existing atmospheric refraction model as described in Reference [1]. The study of this relationship is an isolated problem: an error of the starlight tangential height will not severely affect the effectiveness of other analyses as long as it conforms to reality.

Suppose the Earth's atmosphere is a symmetric sphere, then the starlight refraction angle γ is determined only by the height of the starlight tangential line in the atmosphere from the Earth's surface, which is briefly referred to as the starlight tangential height h_t. Based on the atmospheric density model, the functional relation between the two can be accurately approximated as:

$$\gamma = 2.21 \times 10^{-2} \exp(-0.14 h_t) \tag{4}$$

where the unit of γ is radian, and the unit of h_t is kilometer. For instance, when the tangential height is 25km, the refraction angle will be 137.6 angular seconds.

In the case when two stars are observed simultaneously with the stellar sensor, the angular distance between the two stars will change if one of the stars transmitting through the atmosphere is refracted. The value of this change becomes the starlight refraction angle through the atmosphere. Then, the starlight tangential height h_t can be calculated from the atmospheric model Eq. (4).

Let u_s be the unit vector of starlight, and u be the unit vector vertical to the starlight direction in the plane of the starlight and the satellite location vector

$$\boldsymbol{u} = \frac{(\boldsymbol{u}_s \times \boldsymbol{r}) \times \boldsymbol{u}_s}{|(\boldsymbol{u}_s \times \boldsymbol{r}) \times \boldsymbol{u}_s|} \tag{5}$$

$r(t) \cdot u(t)$ is the projection of the location vector r in the u vector direction, and $r(t) \cdot u_s(t)$ is the vertical distance from the satellite to the u vector line along the u_s direction. From here, the observation equation can be derived as:

$$h_t = \boldsymbol{r}(t) \cdot \boldsymbol{u}(t) - \tan\gamma[\boldsymbol{r}(t) \cdot \boldsymbol{u}_s(t)] - r_e - h_b \tag{6}$$

where h_b is the systematic error in observing the starlight tangential height.

In simulation calculations, the stellar sensor can be simulated, through the iterative solution of equations (4) and

(6), to observe the measurement value of the starlight refraction angle γ and the corresponding observation value h_t.

5. Obscuration Time Observation Model

The precision of the starlight refraction observation is based on the accuracy of the atmospheric model which ranges from 20 to 80 km. It is believed that the accuracy of the model is lower within a wide range than in a small range and therefore, restricting the range of the atmospheric model can help increase the accuracy of the observation value. The limitation of such a restriction is determined at a particular fixed value of the starlight tangential height, usually its minimum height about 20km, when the starlight refraction angle reaches a maximum value, approximately 227.2 angular seconds. In addition, the navigation observation value is determined as t^*, a time when the starlight refraction angle is equal to 227.2 angular seconds. This time, briefly referred to as the obscuration time, is read out by the in-satellite clock and it is believed that the starlight becomes invisible after this time. The equation of the obscuration observation model can be written as:

$$r(t^*) \cdot u(t^*) - \tan\gamma_0 [r(t^*) \cdot u_s(t^*)] = r_e + h_0 \quad (7)$$

where the obscuration time t^* is the solution to the above-mentioned equation, while γ_0 and h_0 in the equation are the foregoing given values.

By using the obscuration time, only one observation value can be derived from one star during one flight around the satellite. In the case when there are few observable stars, the filtering accuracy can be increased through using the iterative method due to the non-linearity of the observation equation.

Apart from the regular iterative method, the following method can also be used for data processing. This method makes use of a preset refraction angle to obtain the obscuration time t^* and then observation time value. To process the data as effectively as with the iterative method, a follow-up fraction of time can also be recorded. Let $\Delta t=t-t^*$ be the observation value, which is the difference between the time of the in-satellite clock and the obscuration time. This time difference can be calculated by using the estimated values of the present location and velocity vector, and the calculations are compared with the time recorded by the in-satellite clock, and the comparison result is used to correct the estimated values of the present location and velocity vector.

Within a small range of time, the satellite location vector can be approximately expressed in the equation as follows:

$$r(t^*)=r(t)-v(t)\Delta t \tag{8}$$

By substituting this equation into Eq. (7) and letting $u(t)-u_s(t)\tan\gamma_0=u(t)$, an imaginary observation equation can be derived as follows:

$$\Delta t=\frac{r(t)\cdot u(t)-(r_e-h_0)}{v(t)\cdot u(t)}+\Delta t_b \tag{9}$$

where Δt_b is the observation error. With the assumption of the approximate Eq. (8), the Δt value can be selected in the range of 5-10 sec.

6. Estimation and Correction of Systematic Errors

The major factors that affect the precision of state estimation include errors of the state model and systematic errors of observation. Systematic errors are not observable under general conditions, but the systematic error in the original observation can become an observable error, as long as a new appropriate means of observation is introduced.

In the starlight refraction observation, the systematic errors involve the systematic error of the stellar sensor and that of the atmospheric model. Since the starlight tangential height is selected as the observation value, these two systematic errors can be regarded as errors of the starlight tangential height. Simulation calculations indicate that this systematic error plays a decisive role in orbit determination precision and thus, it should be estimated.

The automatic satellite navigation system does not exclude short-time support from the Earth-based station. Presumably if the Earth-based station can conduct an accurate satellite orbit determination with a particular method in a short time, this means that the observation value of the satellite location is acquired and the dimension of the observation value in the system state estimation is increased. As for the starlight refraction, apart from the original observation Eq. (6), a new observation equation is added:

$$l=r+l_b \tag{10}$$

where l is the observation value of the satellite location, and l_b is the systematic error in satellite location measurement. It is generally believed that this systematic error can be reduced to a small figure.

7. Simulation Calculations and Their Results

7.1 Original Data

The satellite orbital parameters include: major semiaxis, 7293.27km, eccentricity 0.001809, orbital inclination 65.9^0, right ascension of ascending node 0.0^0, perifocal angular distance 90.0^0 and true anomaly 0.0^0.

The random perturbation error of the orbit location is $1.0x10^{-3}$km, while the random perturbation error of the velocity is $1.0x10^{-6}$ km/sec.

The atmospheric resistance parameter $C_b=6.0x10^{-12}1/m$.

7.2 Simulation of Starlight Angular Distance Observation

Using binary star observations, suppose the constant error of the angular distance observation is 0.001 radian and the systematic sampling period is one second, then following three rounds of observation, the error in satellite location estimation can be converged to 0.6km. The simulation calculations are shown in Fig.3.

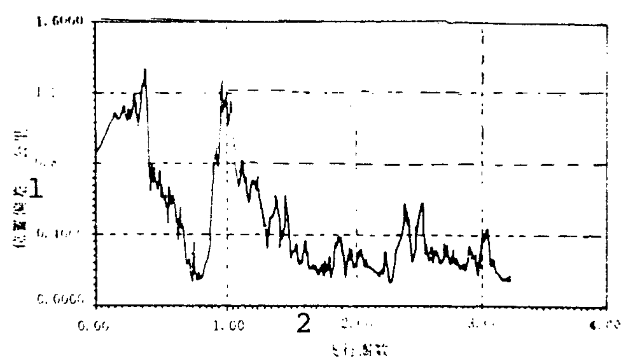

Fig. 3

Key: (1) Location deviation (km)
(2) Number of flight rounds

7.3 Simulation of Starlight Refraction Observation

With 200 stars deployed on the celestial sphere, the backward field flare angle of the stellar sensor is 90^0 and the starlight tangential height is selected between 15 and 80km. In this case, the satellite can observe around 120 stars in one orbital circuit, with each star kept refracted for approximately 20 seconds on the average.

The constant deviation in refraction angle measurement as well as the error of the atmospheric model can both lead to an observation error of the starlight tangential height. Suppose the measured constant error is 0.06km, the systematic sampling period is 2 seconds and the location estimation error is 0.2km, then the results can be seen in Fig. 4.

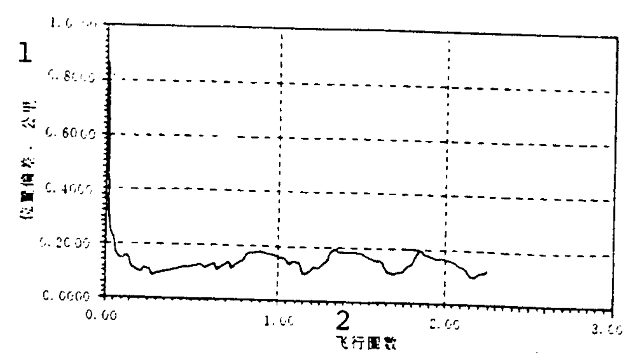

Fig. 4

Key: (1) Location deviation (km)
(2) Number of flight rounds

7.4 Simulation of Obscuration Time Observation

The observation error of the starlight tangential height, determined by the error of the atmospheric model, will give rise to an observation error of the obscuration time. When the constant deviation of the starlight tangential height is 0.06km, the observation constant deviation equivalent to the obscuration time is approximately 0.04 seconds. If the obscuration time interval is picked as 5 seconds, the sampling interval 0.5 seconds and the location estimation error 0.25km, then the results can be seen in Fig. 5.

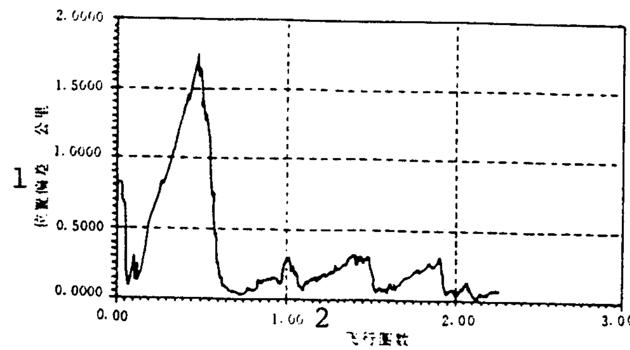

Fig. 5

Key: (1) Location deviation (km)
(2) Number of flight rounds

7.5 Estimation of Systematic Error

Suppose the Earth-based station can arrive at a 5m precision in the satellite location measurement and measurements are conducted every two seconds in the arc period of 15 minutes, then the estimation of the constant error of the starlight tangential height of the atmospheric refraction model can converge to 30m. At the same time, the atmospheric resistance system can also be estimated more accurately as shown in Fig. 6.

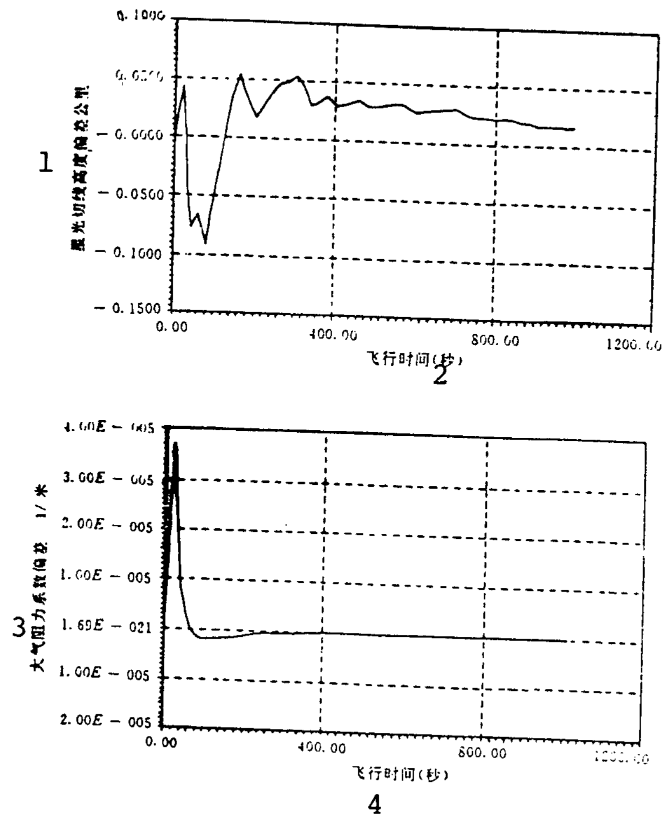

Fig. 6

Key: (1) Deviation of starlight tangential height (km); (2) Flight time (sec); (3) Deviation of atmospheric resistance coefficient (1/m); (4) Flight time (sec)

8. Conclusions

The major systematic error in the starlight angular distance observation is caused by inaccurate determination of the geocentric vector in the intrinsic coordinate. The minimum constant deviation calculated by infrared sensor or other devices may arrive at 0.001 radian order of magnitude. This kind of model fails to feature the highest precision that a stellar sensor can reach.

According to some foreign information sources, the atmospheric model error is basically seasonal, and the atmospheric refraction model can approach an adequate accuracy. Converted to the starlight tangential height, the measurement deviation can be limited within 0.07km as seen in Reference [1]. At this measurement level, the starlight refraction method and obscuration time method are superior to the angular distance method in terms of navigation accuracy, while the starlight refraction method is roughly equivalent to the obscuration time method in this aspect.

Both the starlight refraction method and obscuration time method are greatly affected by the atmospheric model. In other words, it is vitally important to determine the atmospheric model, and automatic navigation free of assistance from the ground can lead to low accuracy. With the help of the accurate orbit determination by an Earth-based station, corrections can be made to the systematic errors from both the starlight refraction method and obscuration time method in the 15 minutes observation arc period. Incidentally, the effectiveness of such correction is found to be associated with the atmospheric refraction model, which, therefore, is worth further studies.

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