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Effects of Atmospheric Forces on Satellite Orbit

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ABSTRACT

The Satellite orbit determination approach involves the set of techniques which measure the satellite motion in term of velocity and position. In this paper, we have discussed various methods for determining an accurate ephemeris for an orbiting satellite which involves estimating the position and velocity of the satellite from a sequence of observations. To study the effect of perturbations on the characteristics of the orbit due to different type of gravitational and non- gravitational forces, we have applied diverse prediction algorithms and analyzed the changes in the Keplerian elements. The applied techniques for orbit determination are Kalman Filtering, Gauss Theory, and Force model. Several Dynamic and static errors are the performance limiting factor for estimation techniques, such as the geopotential model errors and atmospheric drag model errors, depending on the environment of the user satellite.

Keywords: GNSS, Orbit determination, EKF, Non-Gravitational forces, Gravitational Forces.

1. INTRODUCTION

The main requirement of the Orbit Determination is to find out the position of the object in space and its motion in the various directions, in order to find the actual position and drift. The inter satellite communication is the trend through which the neighboring satellite provides the actual position of other satellite to assist the ground station for retaining control over the satellite [1]. For the Global Navigation Satellite, consider the MEO constellation which includes bunch of 24 satellites and the 3 orbital distributions with 55 degree inclination angle [3]. The orbit determination process constitutes of various signal processing and detection procedures which estimate the drift and predict the future orbit. Various methods have been devised for orbit determination in the last few decades such as Kalman filtering, Extended Kalman filtering, and Gauss Method. The dynamic orbit determination is achieved by high prediction ability of the earth orbiters which is used in conjunction with GPS to provide a more accurate solution than Global Navigation System [1].

The requirement of Orbit Determination exists due to Gravitational and Non-gravitational pull which drift the satellite from the actual path instead of what is provided by the Earth station. The gravitational pull constitutes of Centripetal and Centrifugal force whereas the Non gravitational pull constitutes of atmospheric drag, solar radiation pressure, third-body perturbations, and Earth tidal effects [8]. For the Global Navigation Satellite, Orbit determination is generally associated to two coordinate system: the earth centered earth fixed and earth centered inertial system which provides the coordinates of the satellite as well other object establish in the space [1]. To predict the future orbit, the satellite orbital parameters should be calculated first followed by finding the coordinates of the satellite. The satellite orbital Keplerian motion is mainly defined by the six orbital parameters which are provided in Table 1.The Global Navigation Satellite System is established in the MEO and the mean distance from the middle of the earth is 26,560 km. With a mean earth radius of 6360 km, the height of the MEO (Medium Earth Orbit) is about 20,200 km. [5]

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The paper is organized in sections: Section 1 gives the introduction about orbit determination of satellite, whereas various techniques for orbit determination is described in section 2 followed by discussion on orbital perturbations in section 3 and finally conclusions in section 4.

2. TECHNIQUES OF ORBIT DETERMINATION

There are three parameters which depend on satellite motion with respect to earth i.e. distance, velocity and angle. In order to deduce the orbit of satellite, six parameters are required which are given in Table 1. There are various methods to determine the orbit of satellite like Least square method, Laplace method, Gauss method whose principle methods and few features are mentioned in Table 2.

Table 1
Six Orbital Parameters for Determination

Notation	*Keplerian Parameter*
a	Semi-major Axis
e	Eccentricity
i	Inclination Angle
w	Argument of Perigee
Ω	Right Ascension of Ascending Node
M	Mean Anomaly

2.1. Least Square method

This method is used to enhance the reliability in Orbit determination because it takes more and more observations before the prediction. There are two main types of Least square methods: Batch least square method and Kalman filtering method. In batch square method, all the required data is first collected and then processed but in Kalman filtering, the state vector is used for better estimations [8].

2.1.1. Batch least square method

Commonly the weighted factor is applied to each residual term but in batched least square, all the data is collected in single unit for processing. The general description of this method is:

Let the time independent vector as ‘x’, which is n-dimensional and has knowledge of satellites velocity and position along with other two parameters ‘p’ and ‘q’. The force and measurement models are affected by these two parameters ‘p’ and ‘q’. The measurements taken at individual *epoch* is defined by m-dimensional vector y. The basic equations [8] are:

$$x(t) = \begin{bmatrix} r(t) \\ v(t) \\ p \\ q \end{bmatrix}, \quad y = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} = h(x_0) + \rho \tag{1}$$

Where ‘h’ denotes the values at reference *epoch*, ‘ρ’ is the difference between modeled and actual values.

2.1.2. Kalman filtering

Rudolf Kalman developed a technique to estimate the orbit of satellite which is famous with the name of *Kalman filtering* [9]. The technique performs various types of measurements to observe the orbit and altitude of satellite. Its algorithm consists of two main phases: (i) prediction phase (ii) correction phase:

(i) Prediction phase - The algorithm in this state uses various models to predict the systems state over time. The models works upon mathematical equations of motion of an orbiting satellite.

(ii) Correction phase - The Kalman filtering is applied to the system which uses linear equations of motion. The state transition matrix is used to propagate the state and its error linearly. To determine the orbit, the satellite velocity and position is made as the state vector but to determine the altitude, the state vector is made of angles. The state vector for orbit determination is: $x(t) = [r_i\ r_j\ r_k\ v_i\ v_j\ v_k]^T$ and for altitude determination is: $[\theta_1\ \theta_2\ \theta_3\ \dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3]^T$. The observation matrix for orbit determining is:

$$H=\frac{\partial z}{\partial x}=\begin{bmatrix} \frac{\partial r_i}{\partial r_i} & \frac{\partial r_i}{\partial r_j} & \frac{\partial r_i}{\partial r_k} & \frac{\partial r_i}{\partial v_i} & \frac{\partial r_i}{\partial v_j} & \frac{\partial r_i}{\partial v_k} \\ \frac{\partial r_j}{\partial r_i} & \frac{\partial r_j}{\partial r_j} & \frac{\partial r_j}{\partial r_k} & \frac{\partial r_j}{\partial v_i} & \frac{\partial r_j}{\partial v_j} & \frac{\partial r_j}{\partial v_k} \\ \frac{\partial r_k}{\partial r_i} & \frac{\partial r_k}{\partial r_j} & \frac{\partial r_k}{\partial r_k} & \frac{\partial r_k}{\partial v_i} & \frac{\partial r_k}{\partial v_j} & \frac{\partial r_k}{\partial v_k} \\ \frac{\partial v_i}{\partial r_i} & \frac{\partial v_i}{\partial r_j} & \frac{\partial v_i}{\partial r_k} & \frac{\partial v_i}{\partial v_i} & \frac{\partial v_i}{\partial v_j} & \frac{\partial v_i}{\partial v_k} \\ \frac{\partial v_j}{\partial r_i} & \frac{\partial v_j}{\partial r_j} & \frac{\partial v_j}{\partial r_k} & \frac{\partial v_j}{\partial v_i} & \frac{\partial v_j}{\partial v_j} & \frac{\partial v_j}{\partial v_k} \\ \frac{\partial v_k}{\partial r_i} & \frac{\partial v_k}{\partial r_j} & \frac{\partial v_k}{\partial r_k} & \frac{\partial v_k}{\partial v_i} & \frac{\partial v_k}{\partial v_j} & \frac{\partial v_k}{\partial v_k} \end{bmatrix} \quad (2)$$

2.2. Extended Kalman filtering

In extended Kalman filtering, the state transition matrix is calculated at every instance of time instead of being calculated at initial state of algorithm only. The satellite position is used to calculate the state transition matrix again and again with time. This technique reduces the error in orbit determination process but somewhat expensive than its predecessors.

Table 2
Various techniques of orbit determination

Year	*Technique used*	*Ingredients*
2011 [13]	Sigma point Kalman filtering and Extended Kalman filtering.	• The sigma point Kalman filtering is more robust than EKF • It has faster convergence.
2012 [11]	Gauss method	• Faster process for Orbit Prediction • Reduced number of iteration significantly • Improves the accuracy without increasing the iterations
2014 [10]	Extension of Gauss method	• All perturbations are considered to reduce errors • Reduces the statistical errors • Better estimation ability.
2014 [12]	Extended Kalman filtering (EKF) & Least Square (LS) method	• EKF is faster than LS method • EKF is more accurate than LS • Recursive in nature

2.3. Gauss method

Laplace method is insufficient to observe weak orbital elements. The reason of such limitation is the approximation of Taylor series which is used to obtain the derivatives of radius vector. The Gauss method produces more accurate results because it makes the approximation of only dynamics of motion and not of the geometry. As compared with Laplace method, the error propagation is more stable.

3. NON-GRAVITATIONAL & GRAVITATIONAL FORCES EFFECTS ON ORBIT OF SATELLITE

The perturbation arises because of motion of earth satellite due to non-gravitational forces. There are two main categories: atmospheric drag and radiation pressure, which is further categorized into direct solar radiation pressure and re-radiation of the earth. These forces affect the satellite's shape and orbit. The main equation which covers all the effects of perturbations is given as:

$$a_{non-gravitational} = P_{drag} + P_{solar} + P_{earth} + P_{thermal} \tag{3}$$

Where

P_{drag} = perturbations due to atmospheric drag

P_{solar} = perturbations due to solar radiation pressure

P_{earth} = perturbations due to earth radiation pressure

$P_{thermal}$ = perturbations due to thermal radiation

3.1. Atmospheric drag

An arbitrary shaped satellite near to earth moving with velocity in an atmosphere which has atmospheric density ρ experiences the drag force [9]. The mathematical representation is given in equation 4:

$$P_{drag} = -\frac{1}{2}\frac{\rho C_d A}{m} v^2 \tag{4}$$

Where

ρ is atmospheric density

m is mass of the satellite

A is cross sectional area

v is velocity of the satellite

C_d is drag coefficient

The part $\frac{C_d A}{m}$ of equation 4 is ballistic coefficient. There are various models used to describe the atmospheric density. The density has error percentage in the range of 10% to 200% and it depends on solar activities [5]. Some models which are used in the past to measure the density are: Jacchia 71[8], Jacchia 77[9], DTM-2000[10] and the drag temperature model [8]. The deviations in density due to perturbations, from the computed values of density ρ_c is observed. The affected density due to these parameters is evaluated on per revolution basis and given in equation 5:

$$\rho = \rho_c\,[1 + C_1 \cos(M+\omega) + C_2 \sin(M + \omega)] \tag{5}$$

Where

C_1 and C_2 are the once per revolution density coefficient

M is mean anomaly

ω is argument of perigee

3.2. Solar Radiation Pressure

The constant amounts of photons are emitted by sun per unit time. The radiation pressure at a mean distance of 1 A.U from sun is measured as momentum flux having value of 4.5 ×N/. The solar radiation pressure is given in equation 6 [8, 18]:

$$P_{solar} = -P(1+\eta)\frac{A}{m}v\,\mu \tag{6}$$

Where

P is momentum flux due to sun

η is reflectivity coefficient

A cross sectional area of satellite

v is the eclipse factor (v =1 for satellite is in full sun, v = 0 for satellite is in full shadow and 0 < v < 1 for satellite is in partial shadow)

m is mass of satellite

μ is unit vector pointing from the satellite

3.3. Earth Radiation Pressure

For the orbit determination, only solar radiation pressure is not sufficient to be taken into consideration. The radiation pressure emitted by flux of earth shall also be considered for near earth satellites to determine the orbit precisely. The equation 7 gives the earth radiation pressure [8]:

$$P_{earth} = (1+\eta)\grave{A}\ \frac{A}{mc}\Sigma_{j=1}^{N}[(\tau a E_s \cos\theta_s + eM_B)r']_j \tag{7}$$

Where

η satellite reflectivity for earth radiation pressure

$\grave{A}$ is attenuated area of earth

A is cross section area

m is mass of satellite

c is speed of satellite

τ is 0 or 1(darkness or daylight)

N is total number of segment

a is albedo

E_s is solar momentum flux density

M_B is existence of earth

r′ is unit vector from center of element j

3.4. Thermal Radiation

The temperature on surface of satellite is not uniform due to internal and external heat fluxes which gives birth to a perturbation. This effect depends on orbit properties, shape, thermal property and thermal environment of satellite [16, 17].

3.5. Centrifugal and Centripetal force

The centrifugal and centripetal forces are called as pull forces which forces the satellite to deviate from its path. These gravitational forces when act together on the satellite, indirectly helps to retain the orbit of the satellite. The centripetal force is a real force which is described as a component of force acting on a body in curvilinear motion that is directed toward the center of curvature and the centrifugal force is apparent force, it is equal and opposite to the centripetal force. It can be analyzed from figure 1 that centripetal and centrifugal force is equal in magnitude and opposite in direction.

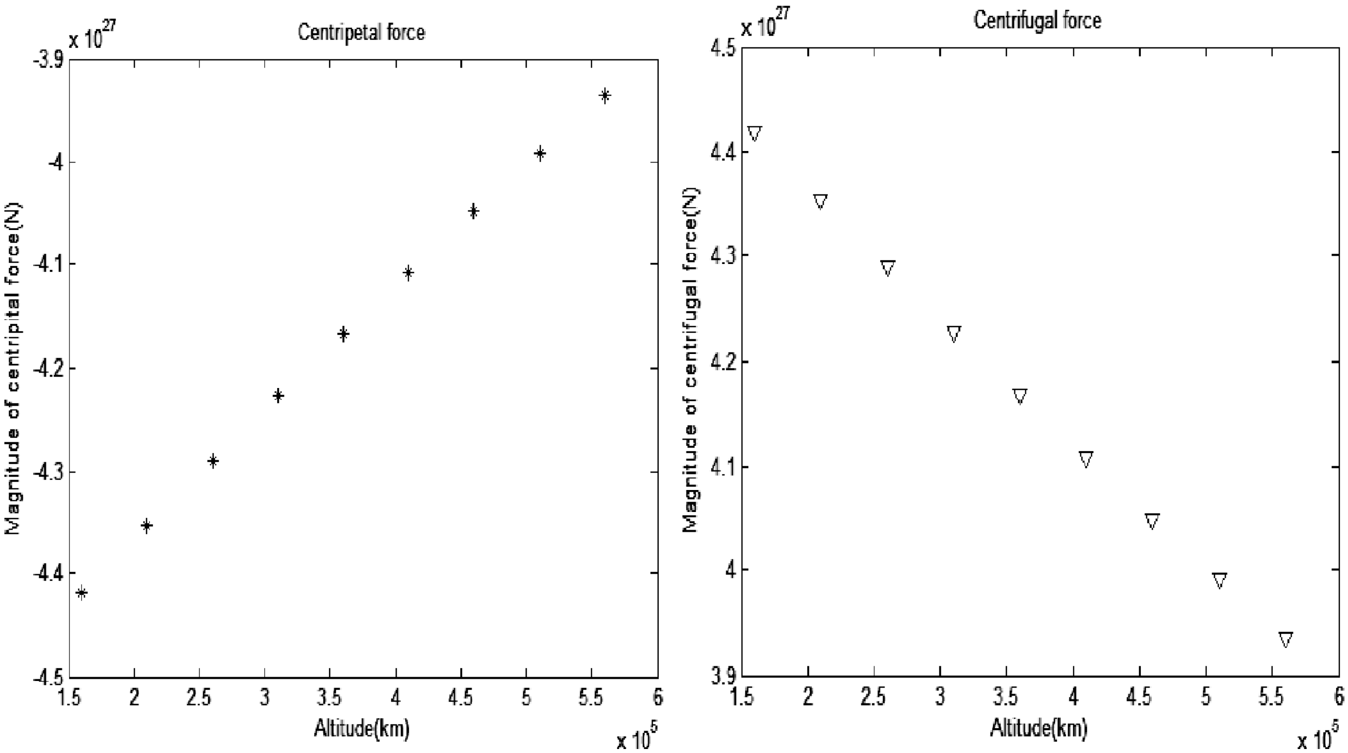

Figure 1: Impact of Centripetal & Centrifugal force on Altitude of Orbit

Table 3
Effected Orbital Parameters due to Atmospheric forces

Atmospheric Forces	*Deviated Orbital Elements*
J2 Perturbation	Mean anomaly, Right ascension for ascending node, Argument of perigee
Atmospheric Drag	Semi-major axis. Eccentricity, Right ascension for ascending node, Argument of perigee
Solar radiation Pressure	Semi-major axis, eccentricity, Mean anomaly
Centripetal and Centrifugal	Semi-major axis, Eccentricity

In figure 2, the effect of gravitational force on latitude and longitude of satellite orbit is analyzed with respect to time (days). From the figure, it is observed that continuous presence of these gravitational forces lead to a considerable deviation of satellite from its initial coordinates. Table 3 points out the effect of the forces on Keplerian elements.

4. CONCLUSION

The orbit determination is an important aspect in satellite communication. The position and velocity of satellite in a particular orbit is observed by orbit determination techniques. The inter satellite link is also

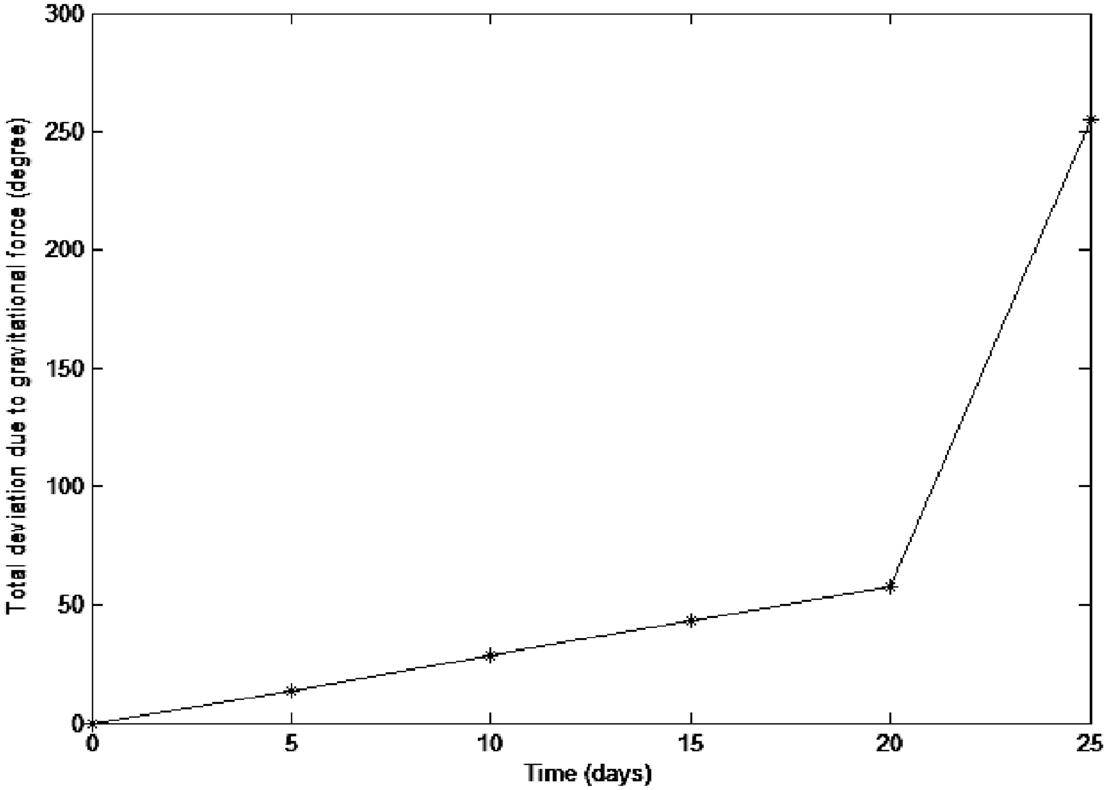

Figure 2: Variation of latitude and longitude due to Gravitational forces

used in which a neighboring satellite is used to find the exact position of target satellite. There are several other method including least square, Laplace and gauss method to determine the orbit. The most of work in present research is based on extended Kalman filtering or some extensions of gauss method. It is found from the study that non-gravitational forces such as Atmospheric drag, solar radiation pressure and earth radiation pressure affect the orbit of satellite. The most dominating is atmospheric drag force. These perturbations affect the six elements which are used to describe the orbit of satellite thereby making it mandatory to predict the future orbit of the satellite in order to retain the control over it.

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