ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 9, Issue, 07, pp.54556-54560, July, 2017

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

RESEARCH ARTICLE

THEORETICAL EXPLANATION AND CALCULATION FOR ORBITAL PERTURBATIONS IN GEOSTATIONARY ORBIT

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ARTICLE INFO

Article History:
Received 20th April, 2017
Received in revised form
11th May, 2017
Accepted 18th June, 2017
Published online 31st July, 2017

Key words:

Orbital Perturbation, Umbra, Penumbra, Solar Eclipse, Gravitational, GEO.

ABSTRACT

3/4th of the research work has been done based on selecting an orbit for a communication satellite, delta-V calculation to obtain a low delta-V total for fuel consumption, building required impulsive burns to attain the orbit by the satellite and six keplerian orbital elements to describe the satellite's position and direction in the previous discussions of my paper. In this paper orbital perturbations calculation will be done for various disturbances which affect the satellite's mission. Usually geosynchronous launch vehicle is used to spot the satellite in its particular position. GSLV–F04 of MK.II series is chosen for its perigee and apogee distance because with these values delta-V can be calculated. And along with orbital perturbations, satellites under various environments are also been explained theoretically. Rather than this, general and special perturbations are described briefly to attain perturbations are caused by the changes in the orbital elements and in the velocities, position and acceleration of a satellite.

Citation: Ramya Preethi, S. 2017. Theoretical explanation and calculation for orbital perturbations in geostationary orbit", *International Journal of Current Research*, 9, (07), 54556-54560.

INTRODUCTION

Perturbation begins in the first attempt to predict motions in the sky which was a mystery in ancient times. At that time Newton formulated his laws of motion and laws of gravitation by recognizing the complex difficulties of their calculation. Gravitational perturbations are considered to be a complex motion happened typically at a conical section. These hypothetical motions can be readily described with the methods of geometry. This is called as unperturbed keplerian orbit and a two-body problem. Perturbations occur due to the additional gravitational effects of the remaining body with respect to the actual motion of the body. The perturbed motion is considered to be a three-body problem, if there is only one other significant body and there are multiple other bodies then it is an n-body problem. In two-body problem a mathematical expression is used to predict the positions and motions at any future time and it is known as general analytical solution. One primary body which is dominant in its effects involve multiple gravitational attractions. The desired orbit is usually chosen based on many factors when a satellite is to be launched in an orbit (Cook, G. E. (Vol. 6, No. 3, April 1962)). For a lot of active satellites, the orbit of satellite must therefore be maintained accurately. In a geostationary satellite it must maintain its latitude and longitude position such that it does not leave its desired position (more than $\pm 0.05^0$in the east-west direction and $\pm 0.05^0$ in the north-south direction) which appears to be fixed in the sky. This responds to a square in space that is roughly 70km in each side at the altitude of a GEO satellite. It appears to be an easy task as this square is huge but in practice this is not true because of many factors.

They are:

1. The slightest forces acting on the satellite is because of weightlessness of objects in space. This means when a small force acting on an object in a specific direction will result in an accelerating the object in that direction. The accumulations of these accelerations become significant over days, months or even years that the satellites may gain relatively high speeds in an undesired direction. Hence from the target region the satellite's location will be moving away.
2. If we assume Earth as a point mass at the centre of its gravity, the Keplerian model for orbital elements is the only try. Clearly, this is not true because:
    - Earth is a non-spherical sphere but it is flatter at the poles than at the equator. Over the equator the Earth's diameter will be greater than the diameter passing over the two poles by approximately 20km.
    - As the satellite move over the equator the radius of the Earth changes.

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- As a satellite moves in its orbit the density of earth is not uniform but has higher values at specific regions, which causes a non-uniform gravitational force.

3. Gravitational forces from the sun and moon acts on the satellite in different directions as their positions respect to the satellite change over the time of the day, month and year. The figure shows the relative inclination of satellites in GEO orbit, the sun and the moon.

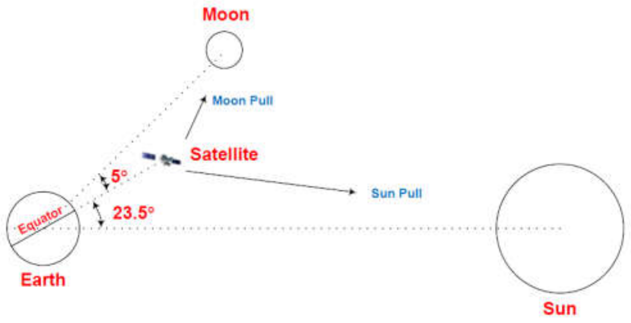

Figure 1. Represents the inclination of satellites in GEO due to the third body in space

4. **Solar Winds:** Basically the sun emits small amount of solar winds and it has been found to have periodic flares once in 11 years. During solar flares huge amount of solar winds are emitted that satellite communications are often interrupted.

General perturbations

General differential equations are used in general perturbations. Changes in the orbital elements are solved analytically by series expansion. The result from these analytic is expressed in terms of algebraic and trigonometric functions. It is not specific to any particular set of gravitating objects and it can be applied to many different sets of conditions. At first general perturbations are investigated and classical methods are described in many names such as variation of the elements, variation of parameters or variation of the constraints of integration. In the above mentioned classical methods, it is considered that the body is moving in a conic section. This section changes constantly due to the perturbations and this conic is nothing but the osculating orbit. Orbital elements at any particular time of this osculating orbit are sought by the methods of general perturbations. In many problems of celestial mechanics, the two-body orbit changes due to the perturbations (it is one of the main advantage of general perturbation). If the perturbation forces are about one order of magnitude lesser than the gravitational force of the primary body, general perturbations are applicable.

Special perturbations

It is a numerical datasets which represents the values for velocities, position and acceleration forces on the bodies. These are made from the differential equations of motion of numerical integration. No attempts are made to calculate the orbital elements or the curves of the orbit because the positions and velocities are perturbed directly. As it is not limited to cases where the perturbing forces are small, so special perturbations can be applied to any problem in celestial mechanics. At first, it only be applied to comets and minor planets but now it is the basis of most accurate machine-generated planetary ephemerides of the great astronomical almanacs. This perturbation is also used for modelling an orbit with computers.

METHODS AND STUDIES

Orbital pertubation

Theoretically, when an orbit is described by the keplerian elements by keeping the Earth as an ideal point considering that the earth to be a perfect sphere. The force acting around the Earth is the centrifugal force. To balance the gravitational pull of the Earth, centrifugal force should act upon it. There are also other forces to play an important role and affect the motion of the satellite. They are gravitational and non-gravitational forces.

Orbital perturbation determination

It is an analysis to determine why a satellite's orbit differs from the mathematical ideal orbit. In the Solar system, all celestial bodies follow the first approximation of Kepler orbit a central body (sun). For a satellite, this central body is the Earth. Due to gravitational forces caused by the Sun, Moon other celestial bodies and due to the flattening of the earth, the satellite will follow an orbit around the earth that deviates more than a keplerian orbit deserved for the planet. Orbital perturbations are been calculated in order to determine the lifetime of a satellite and the orbital manoeuvres to be performed.

There are two types of orbital perturbations:

- **Gravitational:** Consideration of the oblateness (non-spherical) of the earth and third body interactions.
- **Non-gravitational:** Like atmospheric drag, tidal friction and solar-radiation pressure.

The main cause of perturbation in GEO is the gravitational attraction. This flow chart represents that there are many types of perturbations that commonly affects the satellite, but the mentioned three perturbations affects the satellites in GEO:

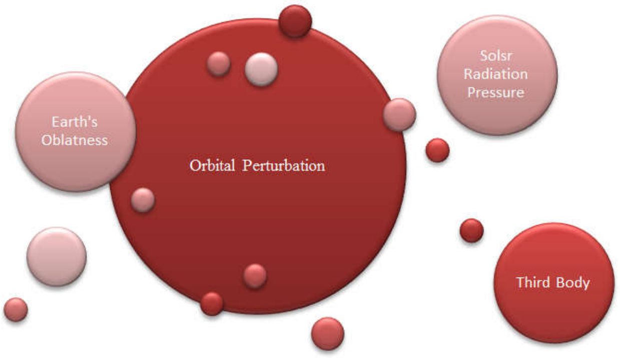

Figure 2. Perturbations affect the satellites in GEO

Effects of non-spherical earth

We all know that the Earth is not a perfect sphere and it causes some kind of variations in the path of the satellite around the planet. Oblateness occurs mainly, the Earth is bulging from the equatorial belt. And we need to keep in account that the orbit is not a physical entity. This force that results from an oblate Earth which acts on a satellite to produce a change in the orbital parameters and it causes the satellite to drift. Further as a result, the regression of the nodes and the latitude of the point of perigee leads to the rotation of the line of apsides. The resultant changes are seen in the right ascension of ascending node and in the values of argument of perigee because the orbit is moving with respect to the Earth. One more effect is been caused by the oblateness of the Earth and this effect is called as "Satellite Graveyard". Due to non-spherical shape of the earth a small value of eccentricity changes (10-5) takes place at the equatorial plane. These eccentricity changes in geostationary orbit makes the satellite to drift to one of the two stable in which it coincides with minor axis of the equatorial ellipse causing a gravity gradient.

Atmospheric drag

The effect of atmospheric drag is more for the satellites in low earth orbit i.e. below 1000km. especially at the point of perigee, the impact of this drag will be more. Drag (pull towards the Earth) has an effect on satellite's velocity by reducing it. Further the velocity reduction causes the satellite not to reach the required height at successive revolutions to apogee. It leads to a change in the value of semi-major axis and eccentricity. By the Earth station, the active satellites are manoeuvred back to their original orbital position.

Station keeping

A geostationary satellite to be kept in its correct orbital slot to control its altitude as mentioned earlier, the equatorial ellipticity of the Earth causes the GEO satellite to drift slowly to one of two stable points at 75° E and 105°W.

Effect of sun and moon

The orbital inclination of a geostationary satellite changes with respect to time by the gravitational attractions of the Sun and Moon. These forces would increase the orbital inclination from an initial $0^{\circ}$to 14.67°. It is been avoided by north-south station keeping, if this inclination not happens in 26.6 years. This problem is not so acute, because no satellite has such a long lifetime.

RESULTS

Perturbation due to solar radiation pressure

Solar radiation is all kind of electromagnetic field emitted by the sun, from X-rays to radio waves. The solar radiation pressure is 4.7×10^{-6} Pa.

The perturbing forces can be calculated by:

$$\frac{a_p}{g_0} = 4.7 \times 10^{-6}(1+\beta)\left(\frac{A}{W}\right)\left(\frac{a_\odot}{r_\odot}\right)$$

a_p= *the acceleration due to the solar radiation pressure*

g_0= *the gravitation at the surface of the earth*

β= *optical reflection constant*

$$\beta = \left\{\begin{matrix} 1\ \text{total reflection (mirror)} \\ 0\ \text{total reception (black body)} \\ -1\ \text{total transmission (transparent)} \end{matrix}\right\}$$

A=*effective satellite projected area*

W=*total satellite weight*=214 0*kg*

$a_\odot$ = semi major axis of the earth′s orbit around the sun $= 1.50 \times 10^{-11} km$

$r_\odot$ = *radius of the earth's orbit around the sun* (*distance of the earth from sun in* 2020) = = 147.2064×10^{10}km

$$\frac{a_p}{g_0} = 4.68172544 \times 10^{-8}$$

So $a_p = 45.91157461 \times 10^{-8} m/sec^2$

Perturbation due to third body

Gravitational forces of the sun and the moon cause periodic variations in all orbital elements. Rate of change of Right Ascension and Argument of perigee due to solar- lunar perturbations are given as:

Right ascension of the ascending node

$$\Omega'\text{MOON} = -0.00338\frac{(\cos i)}{n} = -3.379999 \times 10^{-3}$$

$$\Omega'\text{SUN} = -0.00154\frac{(\cos i)}{n} = -1.539999 \times 10^{-3}$$

Argument of perigee

$$\omega' MOON = 0.00169\frac{(4 - 5sin^2 i)}{n} = 6.75999 \times 10^{-3}$$

$$\omega' SUN = 0.00077\frac{(4 - 5sin^2 i)}{n} = 3.079999 \times 10^{-3}$$

Perturbations due to earth's oblateness

The Earth has a bulge at the equator and flattening at the poles. Rate of change of right ascension of the ascending node and argument of perigee due to earth's oblateness are given as:

$$\Omega' J2 = -1.5nJ2\left(\frac{RE}{a}\right)^2 (\cos i)(1-e^2)^{-2}$$
$$= -0.013431456 \text{ deg/day}$$

$$\omega' J2 = 0.75nJ2\left(\frac{RE}{a}\right)^2 (4 - 5sin^2 i)(1-e^2)^{-2}$$
$$= 0.025807379 \text{ deg/day}$$

Satellite under various environments satellite during eclipses

When the sunlight fails to reach the satellite's solar panel due to an obstruction from the Earth, an eclipse is said to occur. This eclipse is known as the solar eclipse. If the satellite that fails to receive any light from the Sun, then it is considered to be in the umbra region. It is the dark central region of the shadow and it receives very little light when it passes through penumbra region. It is a less darker region surrounding the umbra.

Earth's equatorial plane is inclined at a constant angle of about 23.5 degree with respect to its ecliptic plane during the eclipse. It is the plane of the Earth's orbit extended to infinity. Thus eclipse is seen by the geostationary satellite on 42 nights during spring and an equal number of nights during an autumn. During equinoxes the effect is more and it lasts for about 72 min. (Anil K Maini & Varsha Agarwal. 2010) As explained earlier, equinoxes is the point in time, if the sun crosses the equator makes the day and night times equal. Spring equinox occurs on 20-21 march and autumn equinoxoccurs on 22-23 September. The Earth and the Sun are aligned at midnight as per local time during these equinoxes. Thus it needs to spend about 72mins in total darkness. From 21 days after and 21 days before the equinoxes, satellite used to cross the umbral cone each day for some time, to receive no or only a part of solar light. The GEO satellite passes either above or below the umbral region rest of the year. Time of solstices will be at a maximum distance above the umbral cone at the time of summer solstices between 20-21 June and below the cone at the time of winter solstices between 21-22 Decembers. Therefore starting from 21 days before the equinox, the duration of eclipse increases from zero to about 72 minutes and 21 days after the equinoxes, eclipse decreases from 72 minutes to zero. It is not so acute and occurs once in 29 years. In fact, whenever an eclipse is mentioned with respect to satellites it is considered as a solar eclipse. As the sunlight fails to reach the satellite during the eclipse period, it will be depleted by its electrical power capacity. It can usually continue their operation with a back-up power without affecting the low power satellites. However, the high power satellites will shut down for all essential services.

Figure 3. Umbra and Penumbra [Source: Satellite Communications. Authors: Anil Kumar Maini, Varsha Agrawal, Originally published: April 2010]

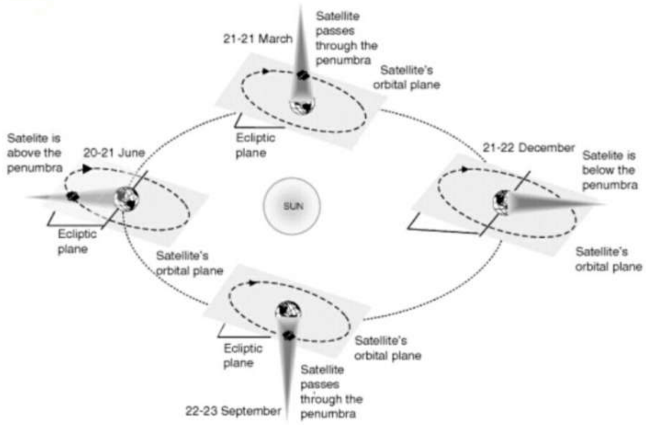

Figure 4. Satellite under solstices and equatorial [Source: Satellite Communications. Authors: Anil Kumar Maini, Varsha Agrawal, Originally published: April 2010]

Variation in the orbital distance

The variation in the range between the satellite and the Earth station terminal, results in the orbital distance variation. If the satellite is been employed by the time division multiple access (TDMA) scheme, the timing of the frames within this scheme should be carefully worked out. Thus the user terminal will receive the correct data from the correct time. In low and medium Earth orbiting satellites range variation is more predominant when compared to the geostationary satellites.

Solar eclipse

When there is an obstruction from a celestial body, the satellite will not receive solar radiation from the sun. During these times, the satellite operates from batteries and on-board them. The batteries should be designed in an appropriate way to provide continuous power during the period of the solar eclipse. To ensure the best performance during the eclipse, ground control stations perform battery conditioning routines prior to the occurrence of the eclipse. This include by fully recharging the batteries just before the eclipse occurs and discharging occurs close to their maximum depth of discharge. Sudden temperature in stress situations creates rapidly when the satellite enters and exists from the shadow of the celestial body. So the satellite is designed in such a manner to cope with these terminal stresses.

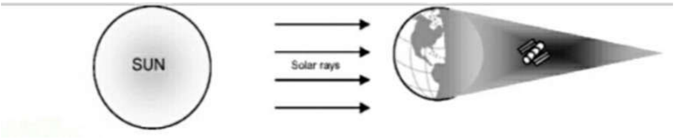

Figure 5. Satellite under Solar eclipse [Source: Satellite Communications. Authors: Anil Kumar Maini, Varsha Agrawal, Originally published: April 2010]

Sun transit outrage

The satellite passes through the Sun and Earth, sun transit outrage occurs. Sun is a source of a radiation with an equivalent temperature which varies between 6000 K and 11000 K depending upon the time of the 11-years sunspotcycle. So the Earth station antenna will receive microwave radiation emitted from the Sun. It is also used to receive signals from the satellite. If the magnitude of the solar radiation exceeds the fade margin of the receiver, temporary outrage must cause at this time. During such periods, the traffic of the satellite might be shifted to the other satellite.

Conclusion

Orbital perturbation is a serious cause in affecting GEO satellites. Thus we saw how disturbances like solar radiation pressure, atmospheric drag and oblateness of earth will affect the satellite's path, mission and lifetime. These perturbations should be avoided in future missions of geostationary satellites, as this satellite does not work in constellation like the satellites in polar orbit. So if a GEO satellite that gets damaged through those perturbations, it can perform with the help of satellites in a constellation. Although there is a principle advantage in a single satellite is that, it reduces the cost by minimizing the mission overhead. On the other hand, the constellation that provides better coverage, more survivability and high reliability if a satellite is lost. To carry out the mission we need to provide multiple conditions such as varying geometrics for navigation, lighting conditions for observations and continuous coverage of a part or all of the earth for communication satellites. Various calculations in perturbations are done above and obtained answers for the required GEO simulation which will be continued further.

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