Impact of solar activity on Low Earth Orbiting satellites

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Abstract. In the present paper, we investigate the impact of solar activity on Low Earth Orbiting (LEO) satellites. How the increase in the number of coronal mass ejections and solar flares raises the likelihood that sensitive instruments in space will be damaged by energetic particles accelerated in these events. So, we study the effect of perturbation forces on the Keplerian orbital elements of two LEO satellites using atmosphere model NRLMSISE00. The equation of motion and the effect of all perturbation are solved by using a High-Precision Orbit Propagation (HPOP) model, with Runge-Kutta 7 method, this method was treated by Cowell’s technique. In this respect we deduce that solar activity influences the upper atmosphere; this influence is mediated through rapid geomagnetic disturbances.

1. Introduction
Low Earth Orbiting (LEO) satellites have physical lifetimes and suffer orbital decay determined almost totally by their interaction with the Earth’s atmosphere. Prediction of LEO satellite lifetimes is of great concern to satellite planners, users, trackers, and frequently to the general public. The prediction of satellite lifetimes depends on a knowledge of the initial satellite orbital parameters, the satellite mass to cross-sectional area (in the direction of travel), and a knowledge of the upper atmospheric density and how this response to space environmental parameters which must also be predicted.

We used a simple model for atmospheric density as a function of space environmental parameters called the atmospheric model and applied it to calculate decay rates and orbital lifetimes of satellites in essentially circular orbits below the altitude of 500 km. Such orbits can be regarded as essentially circular, with the use of the semi-major axis as the orbital radius. The atmospheric density \(\rho\) is specified by a simple exponential with a variable scale height, \(H\). For a fixed exospheric temperature, \(T\), \(H\) is made to vary with altitude, \(h\), through the use of an effective atmospheric molecular mass, \(m\). This \(m\) includes both the actual variation in molecular mass with height and a compensation term for the variation in temperature over the range of 180–500 km. The variation in density due to the space environment is introduced through \(T\) which is specified as a function of the solar radio flux, F10.7, and the geomagnetic index, Ap.

Newton’s second law and his universal law of gravitation are the starting points for virtually any study of orbital motion, especially when combined with Kepler’s laws. His first law states that bodies tend to remain at rest or in uniform motion unless they are acted upon by an external force. Although this idea is easily dismissed in the present time as trivial, it was rebellious in 1687. Previously, theories of motion were based on Aristotelian philosophy. Most scientists believed that an object’s natural state
was at rest because they knew that friction causes objects to impede and eventually stop. The concept of bodies staying in motion was new.

2. Orbital perturbations

There are various sources of perturbations affecting satellite orbital motion from the injection point until the end of its lifetime. In general, orbital perturbations are divided into gravitational and non-gravitational ones. The gravitational ones include the Earth's gravitational force, the Earth’s oblateness, the zonal sectorial spherical harmonics, and the gravitational influences of the Sun and Moon. While the non-gravitational ones include the atmospheric drag force (the dominant for LEO), the solar radiation pressure (effective for geosynchronous satellites), and magnetic forces (due to the interaction of the Earth’s magnetic field with the dipole moment which motivated in the satellite). The gravitational potential of the non-spherical Earth models was initiated by a short period and long period perturbations [1].

Since the propagation of the two-body motion results in the increase of errors as the time of propagation increases, it is better to replace the two-body equation (equation (2.1)) with equation (2.2) that includes all perturbation forces. \( r \) is the position vector of the satellite measured from the center of the primary body, \( \mu \) is the gravitational constant, and \( a_p \) is the sum of all the perturbing accelerations.

\[
\ddot{r} + \frac{\mu}{r^3} r = 0 \tag{2.1}
\]

\[
\ddot{r} = -\frac{\mu}{r^3} r + a_p \tag{2.2}
\]

We only used the drag force and investigate its effect on LEO satellites as shown in table 1. Our results are approximately the same as that found by [2].

| Table 1 | The initial orbital elements for two satellites. |
|---------|---------------------------------------------|
| a (m)   | e   | I(deg) | Ω(deg) | ω(deg) | M         |
| Air drag| 0.058 | 10\(^{-7}\) | 10\(^{-7}\) | 10\(^{-7}\) | 4.5 × 10\(^{-4}\) | Periodic |
| Secular periodic Secular Secular Complex |

2.1. Acceleration due to atmospheric drag

The atmospheric drag is the most complex and the most difficult force acting on LEO satellites. Drag is the resistance exhibited by the atmosphere to the satellite. It acts in the opposite direction of the satellite motion. It was greatest during the launch and reentry. With time, the action of drag on the satellite will lead to spiral back into the atmosphere, eventually to disintegrate or burn up. If the space vehicle comes within 120 to 160 km of the Earth's surface, atmospheric drag will bring it down in a few days, with final disintegration occurring at an altitude of about 80 km [3][4].

Accurate modeling of atmospheric forces is difficult from three points of view. Firstly, the physical properties of the atmosphere, in this case especially the density of the upper atmosphere, are not known very accurately. Secondly, the modeling of these forces requires detailed knowledge of the interaction of neutral gas, as well as charged particles, with the different spacecraft surfaces. Thirdly, the varying attitude of non-spherical satellites with respect to the atmospheric particle flux has to be taken into account.

Drag changes mainly the semi-major axis and eccentricity of the orbit secularly. There are periodic effects in the other orbital elements and some coupling aspects with the spherical potential. The basic equation for atmospheric drag combines several factors (see equation (2.3)).

\[
F_D = -\frac{1}{2}C_D \rho V^2 S_{Ref} \tag{2.3}
\]
Where $C_D$ is the drag coefficient, $\rho$ is the air density, $V$ is the flow velocity of atmospheric particles, and $S_{Ref}$ is the cross-sectional area of the body normal to the flow.

Numerous assumptions are made when developing atmospheric models, which sometimes lead to large inaccuracies and differences between similar models. One of the big assumptions is associated with the effect of the Extreme Ultraviolet Radiation (EUV) as well as with the geomagnetic index. These indices play a big role in all atmospheric models, regardless of their type. The Solar Flux (EUV) index is usually taken as F10.7. The main reason for this is related to its availability. F10.7 measurements have been done since the 1930s.

The neutral density of the upper atmosphere is regarded as the major source of error in the determination of the drag force. Models of the density in this region are not precise and can vary between 10 and 15% in mean conditions [5].

The drag coefficient is a factor that describes the interactions between the atmosphere and the surfaces of the satellites [6]. Consequently, it can be determined that it depends on the material of the surfaces, orientation, and temperature. Since the temperature in this region is mainly dictated by the amount of solar radiation absorbed (which varies with time), it can be concluded that at different times and altitudes the drag coefficient would have different values. This statement is further supported by research done by Prieto et al. (2014) and Finkleman et al. (2014). Errors, in the determination of the drag coefficient, can be reduced by using sophisticated numerical analysis techniques like DSMC and ANGARA [7].

The level of 10.7 solar flux and geomagnetic activity are very difficult to predict but very important for accurate models. The gravitational attraction of molecules in the atmosphere fundamentally determines its pressure and density. The development of both the static and time-varying models depends on a few basic hydrostatic principles which model atmospheric effects.

Cowell’s method is a special perturbation technique. This method was developed by P.H. Cowell in the early 20th century. It’s been used to predict the return of Halley’s Comet and to determine the orbit of the eighth satellite of Jupiter [8]. This is a very simple method compared to other perturbation methods and is now used most frequently since the power of computing is increasing. Cowell’s method takes the equations and motion with all perturbations and then stepwise integrates them numerically [9].

We study the effect of perturbation forces on the Keplerian orbital elements of two LEO satellites using atmosphere model NRLMSISE00. The equation of motion with the existence of individual perturbation and the effect of all perturbation is solved by using High-Precision Orbit Propagation (HPOP) model, with Runge-Kutta 7 method, this method was treated by Cowell’s technique.

3. Data and Methodology
We used the empirical MSIS model especially the newest revision NRLMSISE00 which developed by the United States Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere. The empirical MSIS models of Hedin provide thermospheric density based on data from several satellites and rocket probes [10]. The model has been revised several times with recent revisions released in 1986, 1990 and 2000.

The inputs of this model include the daily solar flux index F10.7 and the global measure of the geomagnetic activity integrated over 3 hours Kp. The F10.7 index required an 81-day running mean that is a calculated average using the F10.7 values over the previous 162 days, corresponding to 6 solar rotation periods. Each rotation of the sun takes 27 days. This procedure for calculating the F10.7 average effective eliminates variations due to the rotation of the sun.

The output of NRLMSIS model includes the following data:
- Total mass density from satellite accelerometers and orbit determination.
- Temperature from incoherent scatters radar covering 1981–1997.
- Molecular oxygen number density, [O$_2$], from solar ultraviolet occultation aboard the Solar Maximum Mission [11].
We study the perturbation forces on two LEO Satellites with different eccentricity and altitude, as well as the data selected, the data analysis, the analysis results, and discussion. The initial orbital elements for the two satellites are listed in table 2 where \(a\) is the semi-major axis, \(e\) is the eccentricity, \(i\) is the inclination, \(\Omega\) is the right ascension of the ascending node RAAN, \(w\) is the argument of perigee, \(M\) is the mean anomaly, \(m\) is the satellite’s mass, and \(A/m\) is the area-to-mass ratio.

| Satellite no. | \(a\) (km) | \(e\) | \(i\) (degree) | \(\Omega\) (degree) | \(w\) (degree) | \(M\) (degree) | \(m\) (kg) | \(A/m\) (kg/m\(^2\)) |
|---------------|------------|------|---------------|----------------|-------------|-------------|------|-----------------|
| Sat.1         | 6870       | 0.00036 | 87.5       | 266           | 343         | 16.3       | 1000 | 0.0075          |
| Sat.2         | 7435       | 0.013  | 29.6       | 300           | 227         | 131        | 1500 | 0.009           |

Figure 1. The behavior of geomagnetic index Ap in one year.

Figure 2. The behavior of 10.7 solar radio flux (F10.7) in one year.

Figure 1 illustrates how the geomagnetic index Ap varies in one year. It increases and decreases depending on solar activity changes. Figure 2 illustrates how the F10.7 varies in one year. F10.7 was maximum at the beginning of this year then decreased smoothly to the end of this year, maybe it was the year of the maximum solar cycle. We investigate the relationship between Ap and F10.7 index and account the correlation coefficient (R) value equal to 0.196, where \(R^2 = 0.0386\). The atmosphere model NRLMSISE00 depends on the Ap index and F10.7 in calculating the thermospheric density.

3.1. Algorithms for orbit propagation

The algorithms for orbit propagation are as follows:

1. Read the orbital elements of satellites from 2-line elements (TLE).
2. Convert the satellite’s orbital elements to position vectors (r) and (v).
3. Solve the equation of motion in case of a 2-body problem.
4. Calculate the components of the drag perturbation force.
5. Solve the equation of motion of satellites under the effect of perturbation force using numerical method (Cowell’s technique).
6. Convert r and v to orbital elements.
7. Calculate the satellite’s orbital decay.
8. Plot the variation of orbital decay with time.

3.2. Study on the effects of the perturbation forces on LEO Satellite 1
Figure 3a illustrates how the semi-major axis for the first satellite changes during the year of 2014. The semi-major axis decreases slowly from 6870 km at the beginning of 2014 to 6833 km at the end of 2014 which indicates that the variation is secular from 6870 km to 6833 km. Figure 3b shows the behavior of eccentricity for the first satellite during the year of 2014. The eccentricity increases from $3 \times 10^{-4}$ in April 2014 to $7 \times 10^{-4}$ in August 2014 then decreases rapidly to zero at the end of 2014. This means that the variation is periodic between zero and $7 \times 10^{-4}$.

Figure 3c shows the behavior of the inclination, the right ascension of the ascending node, and the argument of perigee for the first satellite during the year of 2014. The inclination remains constant at 87.5 degrees during this year but the argument of perigee increases slowly then remains constant for a long duration and then decreases suddenly from 343 to 160 degrees at the end of the year. The right ascension of the ascending node remains constant at 266 degrees.

Figure 3d shows the behavior of the height of apogee and the height of perigee for the first satellite for five years. The eccentricity satisfies a periodic change between $7 \times 10^{-4}$ and zero during the years of 2014 to 2019. The height of perigee decreases slowly from 490 km at the beginning of 2014 to 300 km near the middle of 2018 then it suddenly decreases to 90 km in the middle of 2018. The height of the apogee displays the same behavior as the height of perigee. This indicates that the variation of the height of apogee and the height of perigee for the first satellite during five years is secular from 490 km to 90 km.

3.3. Study on the effects of the perturbation forces on LEO Satellite 2

Figure 4a illustrates how the semi-major axis for the second satellite changes during this year (2014). The semi-major axis decreases slowly from 74354 km at the beginning of 2014 to 7434.9 km at the end of 2014. This is a secular variation from 74354 km to 7434.9 km. Figure 4b shows the behavior of eccentricity for the second satellite during one-year 2014. The eccentricity increases from 0.013000 in January 2014 to 0.01301 in March 2014 then decreases slowly to 0.012998 in June 2014 and returns to...
increase again to 0.013009 in September 2014 then decreases slowly to 0.012997 at the end of this year. This indicates that the variation of the eccentricity of the second satellite during one year is periodic between 0.012996 and 0.01301.

Figure 4. The behavior of the semi-major axis, the eccentricity, the inclination, the right ascension of the ascending node, the argument of perigee, the height of apogee and the height of perigee for the second satellite.

Figure 4.C: shows the behavior of the inclination, the right ascension of the ascending node and the argument of perigee for the second satellite during one-year 2014. The inclination remains constant at 30 degrees also; the argument of perigee remains constant at 228 degrees and the right ascension of the ascending node remain constant at 300 degrees during this year.

Figure 4.D: shows the behavior of the height of apogee and the height of perigee for the second satellite for two hundred years (2015 to 2215). The eccentricity decreases from 0.01368 to 0.01325 during these years. However, the height of perigee decreases slowly from 955 km to 945 km. The height of apogee also decreases slowly from 1155 km to 1140 km. So, the three parameters suffer a secular variation with different three ranges.

4. Results

Our aim is to investigate the impact of solar activity on LEO Satellites, so we found from the previous discussion the following:

1. For satellite 1: the semi-major axis, the argument of perigee, the height of perigee and the height of apogee suffered a secular variation. But the eccentricity suffered a periodic variation. The inclination and the right ascension of the ascending node remained constant.

2. For satellite 2: the semi-major axis, the height of perigee and the height of apogee suffered a secular variation. But the eccentricity suffered a periodic variation. The inclination, the right ascension of the ascending node and the argument of perigee remained constant.

3. The two LEO satellites had different masses and semi-major axis but they suffered the same periodic variations of the semi-major axis, the height of perigee and the height of apogee with different values.
4. The eccentricity suffered a periodic variation with different values for the two different mass LEO satellites.
5. The inclination and right ascension of the ascending node remained constant for the two different mass LEO satellites.
6. The argument of perigee for a LEO satellite with a mass of 1000 kg suffered a secular variation.
7. The argument of perigee for a LEO satellite with a mass of 1500 kg remained constant.
8. The difference in the mass of LEO satellites affected the behavior of the orbital elements.

5. Conclusion
The above results and discussions can be concluded as follows: Solar activities can influence the thermosphere. Generally, the increased solar activity includes increases in x-ray emissions and extreme ultraviolet from the Sun which produce dramatic effects in the Earth’s upper atmosphere.

This paper assures the opinion that shows the associated atmospheric heating increases both the temperature and density of the atmosphere at many spacecraft altitudes. It reveals that the link between the CME and thermosphere has emerged, and interprets the fact that the electric charges in the solar wind ionize the Earth’s ionosphere. Increases in the number of coronal mass ejections and solar flares raise the likelihood that sensitive instruments in space will be damaged by energetic particles accelerated in these events. These solar energetic particles can also overhang the health of both astronauts and airline travelers in polar routes. This study provided us with a global view of what expected in the future of geomagnetic storms effects on Earth’s magnetic field and hence on the communication.

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