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Quantitative Relationship Analysis of Solar Activities and Orbital Attitudes Decline of LEO Spacecrafts

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Abstract

Periodic solar activities can significantly affect the near-earth space environment, specifically the air density of the outer atmosphere, which in turn disturb the normal operation of the LEO spacecrafts. This paper first reviews past findings of the impacts of solar activities on the outer atmosphere and the performances of LEO spacecrafts during the intensive solar activities; then present a simulation study focusing on orbital attitude decline and the operation lifetime of the LEO spacecrafts as a result of solar activities, which draws a quantitative relationship between the orbital duration of LEO spacecrafts at different initial attitudes and the strength of solar activities.

Keywords

LEO; Solar Activity; Outer Atmosphere; Simulation Study; GMAT; Orbit Prediction.

1. Introduction

1.1 Foundations

Sun, the primary energy source the surface of the earth, can significantly affect the environment near us. Human observations of the sun have a long history and were developed separately in different parts of the world, but the scientific and systemic study of solar radiation emission only started in the recent century. In 1947, in Ottawa, Canada, humans started monitoring and recording the F10.7 index[1], which is the solar radio flux (in units of 10−22W/m2Hz) of 10.7 cm wavelength, or 2800 MHz frequency, observed on the ground.

As illustrated in Fig. 1, this index was found to have a high correlation to the solar cycle, the number of sunspots, solar UV radiation intensity, and visible solar irradiance records, so it became an appropriate indicator of the strength of so- lar activities[1]. For instance, based on continuous observation of 13-month, a linear relationship between the F10.7 index and the number of sunspots(Nsunspot) can be obtained:

$$N_{sunspot} = 1.075 \cdot F10.7 - 61.1 \quad (1)$$

In 1949, based on the previous observations of the periodic solar activities, with mean value correction, McNish and Lincoln developed a new linear regression model which could predict the solar activities one year ahead[2]. The prediction model continuously improved in timescale and accuracy in the following years, making future studies about the impact of solar activities on the near-earth space environment which rely on accurate predictions of future solar activities possible.

In 1965, Jacchia published his research on the physical properties of the outer atmosphere, i.e., the atmosphere at 90-125 km above sea level[3]. Despite this model of atmosphere still had some defects, it proved to be one of the best models at the time it was published and became the basic model for future modifications and improvements. This model was made to have atmospheric density values

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consis- tent with the air drag data recorded by satellites. In 1970, Jacchia published a new set of models which took the drastic variation of temperature and atmospheric density at 120 km into account. This model was further modified by Roberts, who rearranged and turned the implicit functions of atmospheric temperature and density in the Jacchia-1970 model into discrete explicit functions by mathematical approaches[4]. The result Jacchia-Roberts model of the atmosphere will be the atmosphere model used in the simulation study in this paper, and the characteristics of this model will be introduced later in this paper.

1.2 Purpose

Any spacecraft requires a certain orbit attitude to operate normally, while according to Choi et al[5], during the solar maximum (the most active period of the sun), the orbit attitude of an LEO satellite, KOMPSAT-1, declines as many as 37 meters in one single day, which is significantly greater than 0.4-1.4 meters orbit attitude decline of another LEO satellite at roughly the same orbital attitude, KOMPSAT-2, operating in an inactive period of the sun.

Another research conducted in the 1990s, which was the most active period of the sun after humans entering space (the F10.7 peak value could exceed 350), also concluded that a satellite operated on an orbit 500 km above the sea level would have 30 years lifetime if the sun were continuously inactive, while the lifetime would decrease to 2 years if the sun were continuously active in this 2 years (which is possible considering the 11-year solar activity cycle)[6].

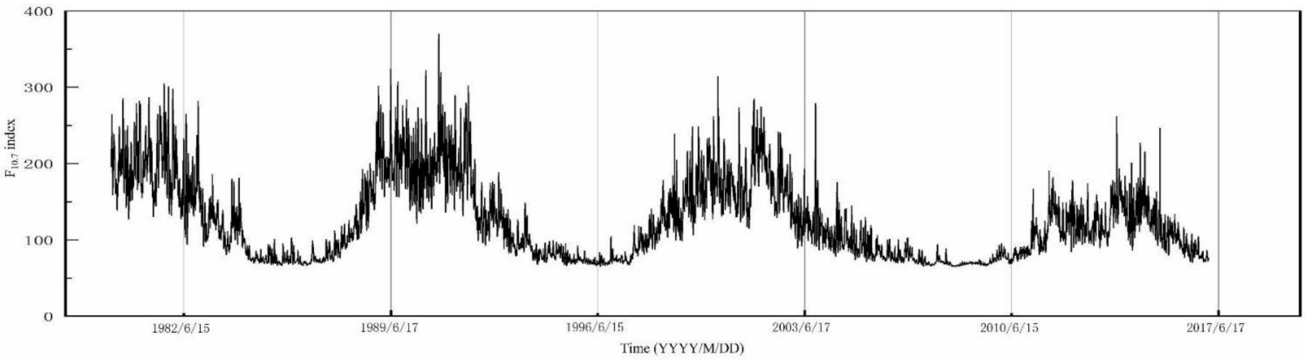

Fig. 1. F10.7 index varies according to the 11-year solar cycle

Therefore, obtaining a quantitative relationship between the solar activities and the variations of the spacecrafts'orbital lifetime can improve the accuracy of the prediction and calculation of the fuel consumptions for the orbital maneuver to offset the effect of solar activities and maintain orbit attitudes. Besides, as more and more spacecrafts entering space, the number of artificial space debris is rapidly increasing and becomes a rising threat to future space programs. Despite there are many ongoing active space debris removal programs, they are far from enough considering the increasing speed of space debris.

As Inter-Agency Space Debris Coordination Committee(IADC) suggested in "Space Debris Mitigation Guidelines"[7], the idea of post-mission disposal of LEO spacecrafts, or specifically, re-entry and being burned up in the atmosphere in 25 years after the mission, should be embodied in the design of future space programs. Because the most influential factor to the orbital duration of LEO spacecrafts is the air density of the outer atmosphere, which is closely related to the solar activity, this article can also contribute to more precise predictions of LEO spacecrafts'orbital lifetimes which is necessary to mitigate the further increase of space debris in the future.

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2. THEORY

Extreme ultraviolet radiation (EUV) is the main cause of the thermal expansion of the outer atmosphere during solar activities. According to Gorney, the strength of solar EUV emission in one solar activity cycle (which is about 11 years) could vary by a factor of 2 in integrated intensity[6].

Because the EUV radiation is almost entirely absorbed by the thermosphere of the Earth, its almost impossible to monitor its variations on the ground, but its high correlation with F10.7 index allows us to approximate it through F10.7, which is observable on the ground.

Some short-period observations of solar EUV irradiance were conducted by rockets or satellites, and one observation result suggested that in one month, from Jan to Feb, 1978, the 10-45 nm band of the solar EUV emission varied 40% and 75-100 nm varied 60%.[8] Comparing to the visible light emission of the sun which only varies less than 0.2%, the variation of EUV emission along the solar activity cycle can result in significant fluctuations of the atmospheric density and temperature of the earth.

More than 20% of the absorbed solar EUV radiation energy is used to bulk heat the thermosphere[9]. Thermosphere, which occupied 85 km to 250 km above the sea level during the inactive period of the sun, could expand up to 500 km above the sea level during the solar maximum. As a result, the expansion of the atmosphere can substantially increase the air drag experienced by the LEO spacecrafts, such as the International Space Station(ISS) operating on the orbit approximately 400 km above the sea level, and therefore either reduce the orbital lifetime or increase the fuel consumption for the orbital maneuver to offset the air drag.

This result is confirmed by the recorded data of accelerometers carried on the LEO satellites: the air drag and air density on the orbit can be calculated from the recorded non-conservative acceleration after subtracting the solar and the earth surface re- flection radiation pressure[10].

Researcher Gorney also drew a qualitative relationship between the satellites' lifetime, F10.7 index, and the satellites'initial attitude: F10.7 index negatively corelates to the satellites'orbital lifetime, i.e., solar activities generally reduce the satellites' orbital lifetime, but satellites with higher initial attitudes are less affected by the variation of F10.7 index[6].

Based on all the past findings introduced above, which built strong theoretical foundations for interactions between solar activities and near earth space environment but were limit to qualitative level, this paper will use a simulation approach to find a discrete quantitative relationship between two independent variables--initial orbital attitudes and F10.7 index--and dependent variable, the orbital lifetime of a typical satellite under a specific condition controlled by two independent variables.

Table 1. GMAT Simulation Initial Parameter Settings

Orbital elements		Satellite parameters	
inclination	96.72°	mass	1.3t
longitude of ascending node	344.955°	Air drag area	$8\ m^2$
argument of perigee	89.9418°	$F10.7$ index	60-240
true anomaly	-89.81°	perturbation	J2 degree 10, order 10

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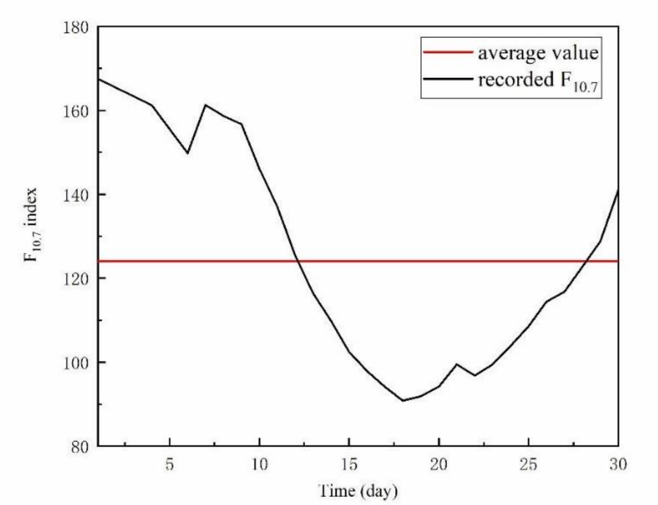

F10.7 indx since Feb. 1, 1983

Fig. 2. To better verify the availability of using

Average values over a month to approximate the continuously varying F10.7 value in the reality, the simulation time interval is also selected to have relatively large F10.7 variations in 30 days: the difference between the maximum and the minimum is 76.7.

3. Application of the Method

This section will introduce the methodology of this paper. The simulation study is conducted on the General Mission Analysis Tool(GMAT), a simulation software with strong space orbit tracking, analyzing, and optimizing capabilities. TABLE. I shows the settings of initial parameters in this simulation study; these parameters, including the size and mass of the satellite, the orbital parameters, are selected according to a representative meteorological satellite, AEOLUS, operating on the circular sun-synchronous orbit. The initial orbit attitudes, as mentioned above, are set to vary between 250 km and 400 km; the F10.7 is set to vary between 90 and 240 on average over a month.

The simulation environment is based on the Jacchia-1970 model[3], which specifies the air density above 125 km as follows: For T∞, the exospheric temperature and Tx, the temperature at the inflection point (125 km), following equation can be used to determine the temperature at attitudes Z, T (Z):

$$T(Z) = T_x + 2(T_\infty - T_x)/\pi \arctan\left(0.95\pi \left(\frac{T_x - T_0}{T_\infty - T_x}\right)\right) \tag{2}$$

Where:

$$C = (1 + 4.5 \times 10^{-6})(Z - Z_x)^{2.5} \tag{3}$$

The equation provides a continuous temperature profile at Zx and by differentiating it, dZ can be obtained. Substitute it together with the value of attitude Z into the diffusion differential equation:

$$\frac{dd_i}{d_i} = \left(\frac{-M_i g_0 R_a^2 dZ}{RT(Z+R_a)^2}\right) - \frac{dT}{T}(1+\alpha_i) \tag{4}$$

where Mi and αi are respectively molecular mass and thermal diffusion coefficient of six constituents of the outer atmosphere: nitrogen, argon, helium, oxygen and hydrogen.

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R = 8.314J/K · mol is the universal gas constant, g0 = 9.80665 m2/s is the acceleration due to gravity and Ra = 6356.766 km is the radius of the earth.

Then di(Z), the amount of molecules per cm3 at attitude Z, greater than 105 km, in moles can be calculated by integrating the diffusion differential equation above:

$$d_i(Z) = d_i(125\ \mathrm{km})\left(\frac{T_x}{T}\right)^{1+\alpha_i+\gamma_i}\left(\frac{T_\infty - T}{T\infty - T_x}\right)^{\gamma_i} \tag{5}$$

Where:

$$\gamma_i = \frac{M_i g_0 R_a^2}{RlT_\infty}\left(\frac{T_\infty - T_x}{T_x - T_0}\right)\left(\frac{Z_x - Z_0}{R_a + Z_x}\right) \tag{6}$$

Therefore the air density above 500 km can be obtained from:

$$\rho(Z) = \sum_{i=1}^{6} Midi(Z) \tag{7}$$

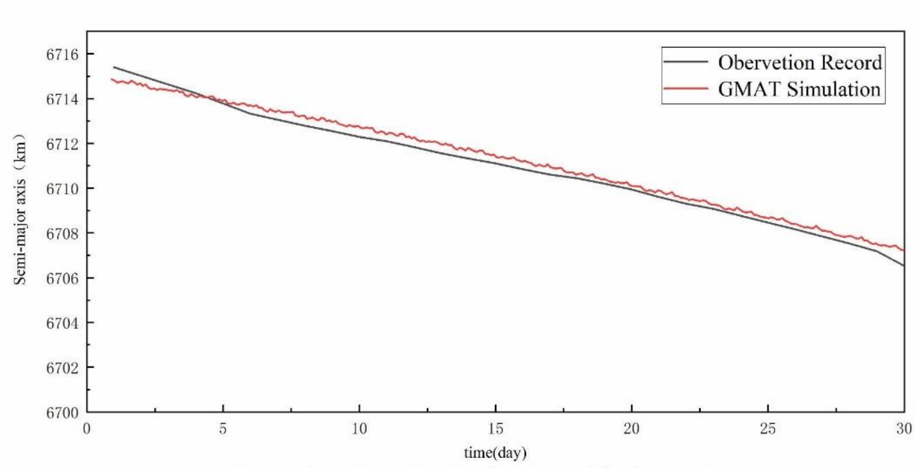

Fig. 3. The discrepancy between the observed orbital data record and the simulated orbital data using the average F10.7 value is less than 1 km over 30 days.

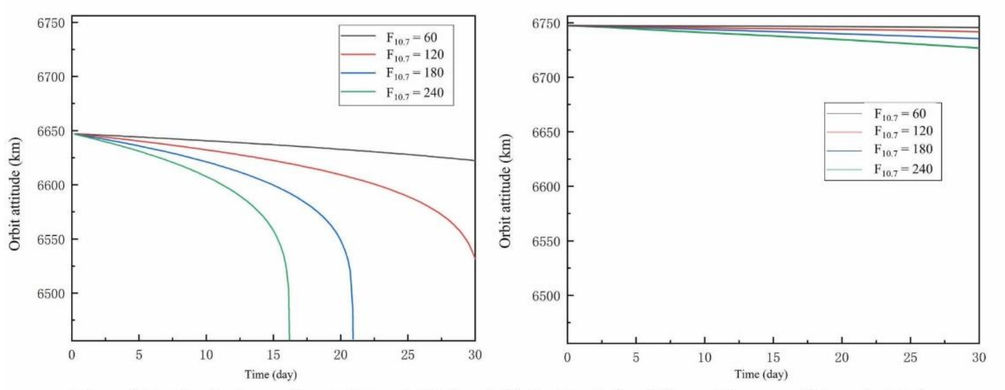

Fig. 4. The impact of F10.7 index on the orbit attitude is very substantial at 300 km initial attitude; but as the initial attitude increases, the impact of F10.7 on the orbit attitude decay decreases.

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Because of the limited simulation ability of the GMAT, the average value of F10.7 over a month is used to approximate the continuously varying F10.7 in reality. To test the availability and precision of this approximation, the orbital data, given by Celestrak, of a space station, Salyut-7, is used to compare with the simulated orbital tracks based on the average value of the F10.7 index. To avoid any disturbance to the simulation result caused by orbital maneuvers of Salyut-7, the orbital data and the F10.7 record are selected specifically in 30 days after February 1983, as shown in the Fig. 2.

The result, as shown in the Fig. 3, indicates that the discrepancy between the orbital data records in reality and the simulation result using the average value approximation is tolerable in this simulation study considering that Salyut-7 is a space station much larger than the targeted satellite studied in this paper and thus is more sensitive to the variation of air drag, which is caused by the variation of F10.7 index. Therefore, this approximation does give the expected simulation result with acceptable precision.

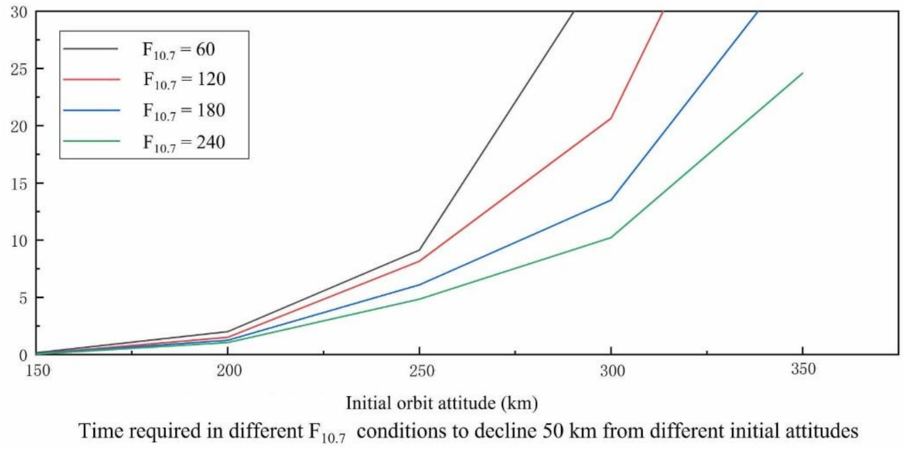

Fig. 5. The figure shows the time needed in different F10.7 conditions to decline 50 km from certain initial attitudes.

4. Conclusion

The results of the simulation are shown in the Fig. 4; on the initial orbit at 300km, F10.7 has a substantial impact on the decline of the orbital altitude: when F10.7 index is 180 and 240, it took the satellite approximately 21 days and 16 days respectively to re-enter the dense atmosphere lower than 100 km, while when F10.7 index is 60, the orbital attitude only declines 25 km.

The simulation is repeated at 325 km, 350 km, and 400 km; the trend that F10.7 has less impact on the satellite at a higher initial attitude is clear. On the initial orbit at 400 km, the satellite reacts to the variation of F10.7 in a distinguishable but limited in magnitude manner: when F10.7 is 60 and 240, the orbital decline is 1.65 km and 20.4 km respectively, which are both insignificant comparing to the orbital decline at initial attitude 300 km. The result could also infer that in 30 days, the variation of F10.7 can hardly affect the satellites on the orbit at 400 km or higher.

As shown in the Fig. 5, it can be seen that when F10.7 is 240, the lifetime of the satellite at 200 km is only 1 day, while the lifetime of the satellite at 350 km is more than 40 days. The qualitative relationship concluded in Gorney's study, solar activ- ities generally reduce the satellites' orbital lifetime, but satellites with higher initial attitudes are less affected by the variation of F10.7 index, coincides with the simulation result very well.

5. Discussions

This simulation study, based on previous findings of the positive correlation between the strength of solar activities and the speed of orbit decay, further investigates the decline of the orbit attitudes from different initial values in different F10.7 conditions and presents the correlation in a more direct and precise way. The quantitative simulation result can have practical implications in spacecrafts' design and orbit control, also provides a reference to the post- mission disposal of LEO spacecrafts.

The limitations of the result include that the time scale of the study is relatively short: 30 days is much shorter than the mission time of a typical satellite; especially for those LEO satellites operating on an orbit above 400 km, 30 days is not enough to show the impacts due to the variation of F10.7 index. Besides, the subject of the simulation study is the specific satellite AEOLUS, whether the behaviors of larger spacecrafts such as space stations or minor spacecrafts such as cubic stars follow the same quantitative relationship is unsure.

Currently human still do not know much about the quantitative mechanism of the way solar activities affects the outer atmosphere. Building an outer atmosphere model which takes the variation of solar activities will be very beneficial to the development of orbital dynamics.

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