Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 47–56

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

# Effects of plasma drag on low Earth orbiting satellites due to solar forcing induced perturbations and heating ☆

Victor U.J. Nwankwo [a,*], Sandip K. Chakrabarti [a,b], Robert S. Weigel [c]

[a] S. N. Bose National Centre For Basic Sciences, Kolkata 700098, India
[b] Indian Centre for Space Physics, Kolkata 700084, India
[c] George Mason University, 4400 University Drive, Fairfax, VA 22030, USA

Received 16 September 2014; received in revised form 14 January 2015; accepted 30 March 2015
Available online 9 April 2015

**Abstract**

The upper atmosphere changes significantly in temperature, density and composition as a result of solar cycle variations, which causes severe storms and flares, and increases in the amount of absorbed solar radiation from solar energetic events. Satellite orbits are consequently affected by this process, especially those in low Earth orbit (LEO). In this paper, we present a model of atmospheric drag effects on the trajectory of two hypothetical LEO satellites of different ballistic coefficients, initially injected at $h = 450$ km. We investigate long-term trends of atmospheric drag on LEO satellites due to solar forcing induced atmospheric perturbations and heating at different phases of the solar cycle, and during short intervals of strong geomagnetic disturbances or magnetic storms. We show dependence of orbital decay on the severity of both solar cycle and phase and the extent of geomagnetic perturbations. The result of the model compares well with observed decay profile of some existing LEO satellites and provide a justification of the theoretical considerations used here.


*Keywords:* Ballistic coefficient; LEO satellite trajectory; Plasma drag; Solar cycle variations; Solar energetic events

## 1. Introduction

Once launched, the optimum performance and survival of a satellite depend on its ability to weather both gravitational and non-gravitational perturbing forces including atmospheric drag, especially for satellites at low Earth orbit. Atmospheric drag on LEO satellites (corresponding to altitudes of $< 800$ km) can cause untimely re-entry of satellites, difficulty in identifying and tracking of satellites and other space objects, manuvering and prediction of lifetime and actual re-entry (Klinkrad, 1996; Mark et al., 2005; Doornbos and Klinkrad, 2006; Xu et al., 2011; Walterscheid, 1989; Nwankwo and Chakrabarti, 2014, 2015). Accelerated orbit decay due to atmospheric drag on low Earth orbiting satellites is mainly due to solar forcing induced variations in thermospheric density profile. There have been studies that investigated the response of thermospheric density and/or satellites orbit to variations in solar forcing due to solar activity using one or combination of several methods such as simulations, satellite drag data, on-orbit mass spectrometers, accelerometers, sounding rockets and ground-based incoherent scatter radars (Klinkrad, 1996; Xu et al., 2011; Burns et al., 2012; Leonard et al., 2012; Kutiev et al., 2013; Lei et al., 2013; Chen et al., 2012; Kwak et al., 2011; Solomon et al., 2012; Liu et al., 2012; Lei et al., 2008; Sutton et al., 2005; Deng et al., 2012; Walterscheid, 1989; Weigel et al., 2004; Weigel, 2010; Nwankwo and Chakrabarti, 2014, 2015). It is known that density of the thermosphere and the vertical

☆ Presented in COSPAR 2014, Moscow, Russia.

* Corresponding author at: S. N. Bose National Centre For Basic Sciences, Kolkata, JD Block, Salt Lake, Kolkata 700098, India. Tel.: +91 33 2335 5706; fax: +91 33 2335 9176.

*E-mail addresses:* victorujn@bose.res.in (V.U.J. Nwankwo), chakraba@bose.res.in (S.K. Chakrabarti), rweigel@gmu.edu (R.S. Weigel).

http://dx.doi.org/10.1016/j.asr.2015.03.044
0273-1177/

extent of the upper atmosphere varies on time scales of solar flare event (few hours), geomagnetic storms (1–3 days) and the solar cycle (~ 11 years) (Alfonsi et al., 2008; Bounsanto, 1999; Kutiev et al., 2013). There is a significant heating and consequent expansion of the upper atmosphere during solar and geomagnetic activities. Studies have shown that solar EUV and thermospheric temperature could increase by a factor of two (or more), and thermospheric density by a factor of up to ten from solar minimum to solar maximum (Emmert and Picone, 2010; Walterscheid, 1989). The contribution to upper atmospheric heating by solar EUV radiation is larger than that associated with geomagnetic current enhancement during time interval of enhanced geomagnetic activity. However, geomagnetic field induced Joule heating becomes important during short-term strong geomagnetic perturbations and can increase by up to 134% when the Kp index increases from 1 to 6 or Ap index from 4 to 80 (Rhoden et al., 2000; Kim et al., 2006; Chen et al., 2012; Kutiev et al., 2013).

Solar energetic events that cause atmospheric heating include solar wind streams, coronal mass ejections (CMEs), solar flares and corotating interaction regions (CIRs). When a solar wind high-speed stream (HSS) emanates from the sun, it interacts with preceding low-speed solar winds and form a corotating interactive region (CIR). The interface between low and high speed solar plasma (CIR) interacts with the Earth's magnetosphere and produces geomagnetic disturbances and storms (Borovsky and Denton, 2006; Burns et al., 2012; Gosling and Pizzo, 1999; Kutiev et al., 2013; Tsurutani et al., 2006). There are many studies which investigated the effects of CIRs or solar wind conditions on the thermosphere and satellite orbits (Burns et al., 2012; Solomon et al., 2012; Liu et al., 2012; Lei et al., 2008; Borovsky and Denton, 2006). CIRs and HSSs are known to be the dominant drivers of storm induced atmospheric perturbations during the declining phase of the solar cycle and are, therefore important to thermospheric density and satellite orbital variations during this phase of the cycle (Burns et al., 2012; Chen et al., 2012; Nwankwo and Chakrabarti, 2014). CMEs and solar flares are sporadic events and are known to vary with phase of a solar 11-year cycle. They are more frequent and intense during a solar maximum (Richardson et al., 2001; Gopalswamy, 2009). Thermal tides propagating upwards from the lower atmosphere can also influence atmospheric density and satellite orbits (Forbes et al., 2009; Hagan and Forbes, 2002; Zhang et al., 2010; Oberheide et al., 2009; Leonard et al., 2012; Nwankwo and Chakrabarti, 2014). Thermospheric density also exhibits annual, semiannual and diurnal oscillations (Emmert and Picone, 2010; Doornbos, 2012).

Some insightful investigations on space weather effects on thermosphere density and satellite orbit includes that of Walterscheid (1989), Chen et al. (2012), Leonard et al. (2012), Lei et al. (2013) and others. Walterscheid (1989) studied effects of the solar cycle on upper atmosphere and their implications on satellite drag and pointed out that a typical satellite initially at a height of 500 km could have a lifetime of about 30 years under typical solar cycle minimum conditions and only about 3 years under the solar maximum conditions (Nwankwo and Chakrabart, 2014). Chen et al. (2012) investigated and compared effects of CIR- and CME-induced geomagnetic activity on thermospheric densities and spacecraft orbits, and found that CME-induced storms (although of shorter duration) causes larger thermosphere density disturbances and a resultant larger orbital decay rates during its main phase than CIR storms, but the mean thermospheric density and satellite orbit decay during CIR storms could be much larger than those during the CME-induced storms in each case because of longer duration of CIR phase. Lei et al. (2013) also studied the impact of solar forcing on thermospheric densities and spacecraft orbits from CHAMP and GRACE satellite's data during the events (CMEs and CIR) of September 14–28 and November 19–22, 2003, and showed that variations of the satellite's semi-major axis was 243 m for CIR-induced perturbations during September 15–27, 2003 and about 130 m for CME-induced storm event during November 19–22, 2003. These studies only used the data (on-orbit mass spectrometers and accelerometers) on existing satellites (e.g. CHAMP and GRACE). In this study, we incorporate the NRLMSISE-00 empirical atmospheric model into our drag model to investigate short- and long-term trends of atmospheric drag effects on LEO satellite orbits due to atmospheric density perturbations and heating by solar energetic events at different phases of the solar cycle. This study is important for understanding how satellite orbits are affected during short- and long-term variations in solar and geomagnetic activity using a realistic atmospheric density and drag model. We are aware of the difficulties associated with exact determination of atmospheric density and orbital predictions at very low Earth orbits. Therefore, we ignore impacts of tidal effects at this stage.

## 2. Upper atmospheric density profile

An accurate prediction of a satellite's lifetime, re-entry or drag depends on good knowledge of atmospheric density profile, which is an important space environmental parameter for satellite operation in the near-Earth space (Kwak et al., 2011; Chen et al., 2012). Although this quantity is not precisely known at any given instant, many atmospheric models have been developed (and more are being developed) over the years with good approximation. However, despite the unprecedented improvements in modeling atmospheric density, concerns about the accuracy of the models remain, because the individual effects of various solar forcing mechanism, which causes fluctuations in neutral and ionized density are very difficult to estimate and/or model (also, see Kutiev et al. (2013), Storz et al. (2005)). Particularly important are the hysteresis effects where the effects of the same event may depend on the history of events which took place before it. Some