Satellite drag effects due to uplifted oxygen neutrals during super magnetic storms

Gurbax S. Lakhina[1] and Bruce T. Tsurutani[2]

[1]Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai, India.
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Correspondence to: Gurbax S.Lakhina (gslakhina@gmail.com)

Abstract. During intense magnetic storms, prompt penetration electric fields (PPEFs) through **E**×**B** forces near the magnetic equator uplift the dayside ionosphere. This effect has been called the "dayside superfountain effect". Ion-neutral drag forces between the upward moving O^+(oxygen ions) and oxygen neutrals will elevate the oxygen atoms to higher altitudes. This paper gives a linear calculation indicating how serious the effect may be during an 1859-type (Carrington) superstorm. It is concluded that the oxygen neutral densities produced at low-Earth-orbiting (LEO) satellite altitudes may be sufficiently high to present severe satellite drag. It is estimated that with a prompt penetrating electric field of ~20 mV/m turned on for 20 min, the O atoms and O^+ ions are uplifted to 850 km where they produce about 40 times greater satellite drag per unit mass than normal. Stronger electric fields will presumably lead to greater uplifted mass.

1. Introduction

Prompt penetration of interplanetary electric fields (IEFs) to the dayside equatorial ionosphere has been known for a long time (Obayashi, 1967; Nishida, 1968; Kelley et al., 1979). It has been shown that during super magnetic storms, defined as storms with Dst< -250 nT (Tsurutani et al., 1992; Echer et al., 2008), the prompt penetrating electric fields (PPEFs) associated with large IEF intervals can last for more than several hours in the ionosphere (Tsurutani et al., 2004; Maruyama et al., 2004; Mannucci et al., 2005; Sahai et al., 2005; Huang et al., 2005). Intense dawn-to-dusk (eastward viewing from the northern hemisphere) PPEFs uplift the dayside plasma to higher altitudes and magnetic latitudes due to **E**×**B** drifts (Tsurutani et al., 2004; 2008; Mannucci et al., 2005; Verkhoglyadova et al., 2007).The ionospheric electron-ion recombination rate is much slower at higher altitudes (Tsurutani et al., 2005), thus the "old" uplifted ionosphere is more or less stable. Solar photoionization replaces the displaced plasma at lower altitudes, increasing the total electron content (TEC) of the ionosphere. After the PPEF subsides, the plasma flows down along the magnetic field lines to even greater magnetic latitudes. This overall process is named as the “dayside superfountain effect”.

During superstorms, the vertical TEC values are found to increase to several times quiet time valuesacross the dayside ionosphere at low and middle latitudes. This has been empirically observed by satellite and from ground-based GPS (Global Positioning System) receivers. Apart from the dayside superfountain effect, which occurs during the first few hours of a superstorm, there is another mechanism called the "disturbance dynamo"(Blanc and Richmond, 1980; Fuller-Rowell et al., 1997). The latter is caused by particle precipitation and atmosphere heating in the auroral zone during the superstorms and consequential equatorward-directedneutral winds due to this heating process. However, all superstormsare not alike as they have different peak intensities and associated convection electric fields(Gonzalez et al., 1994). Therefore, the PPEFs produce different effects in terms of TEC enhancements, poleward-shifting of equatorial ionization anomaly (EIA) peaks (Namba and Maeda, 1939; Appleton, 1946) from the typical quiet time positionsat ~ ±10°, compositional changes, etc. Studies of the Bastille day (15 July 2000) superstorm (Basu et al., 2001, 2007; Kil et al.,2003, Yin et al., 2004; Rishbeth et al., 2010), the Halloween (30 October 2003) superstorm (Tsurutani et al., 2004, 2007, 2008; Mannucci et al., 2005;Verkhoglyadova et al., 2007), and some other superstorms events (Foster et al., 2004; Lin et al., 2005; Immel et al., 2005; Mannucci et al., 2008, 2009) clearly illustrate the above point.

Using a modified version of the low- to mid-latitude ionosphere code SAMI2 (Sami2 is Another Model of the Ionosphere) of the Naval Research Laboratory (NRL) (Huba et al., 2000, 2002), Tsurutani et al. (2007) have studied the O^+ ion uplift in the dayside ionosphere due to first ~ 2 hours of PPEFs during the 30 October 2003 (Halloween) superstorm. Their simulations clearly show the dayside O^+ ions uplifted to higher altitudes (~600 km) and higher magnetic latitudes (MLAT) (~ ±25° to 30°), forming highly displaced EIA peaks. The rapid upward drift of the O^+ ions causes neutral oxygen (O) uplift due to ion-neutral drag forces. They also find that above ~400 km altitude, the neutral oxygen atom densities within the displaced EIAs increase substantially over their quiet time values.

Recently, Tsurutani et al. (2012) have modeled the 1-2 September 1859 Carrington storm using the modified SAMI2 code (Verkhoglyadova et al., 2007, 2008). This superstorm's intensity was the highest in recorded history, Dst ~ -1760 nT (Tsurutani et al. 2003; Lakhina et al. 2012). The storm-time electric field has been estimated to have been ~20 mV/m. Similar features to the 30 October 2003 storm were found, but all effects were more severe. The EIAs were found to be located at ~500 to 900 km altitude with broad peaks located at ~ ±25° to 40° MLAT. In this paper, we study the uplift of neutral oxygen O atoms due to the ion-neutral drag force during an 1859-type superstorm. The possible satellite drag effects on Low Earth Orbiting (LEO) satellites will be discussed.

2. Change in neutral O atom densities due to ion-neutral drag

When O^+ ions drift rapidly upwards through the neutral atmosphere(under the influence of an **E**×**B** force associated with the PPEFs during an 1859-type superstorm), they exert an ion-neutral drag force on the neutral atoms and will uplift them (Tsurutani et al., 2007). A simplified ion-neutral momentum exchange is given by (Baron and Wand, 1983; Kosch et al., 2001):

$$\frac{\partial U}{\partial t} = \frac{1}{\tau_{in}}(V_d - U) \qquad (1)$$

where U is the vertical speed of the neutral oxygen atom due to ion-neutral drag force, $V_d = \mathbf{E}\times\mathbf{B}/B^2$ is the O^+ vertical drift due to the **E**×**B** force, and τ_{in} is the ion-neutral coupling time constant (Killeen et al. 1984) given by:

$$\tau_{in} = \frac{n_0}{n_i\,\nu_{\mathrm{in}}} \qquad (2)$$

In Eq. (2), n_o is the neutral oxygen O atom density, n_i is the O^+ ion density, and ν_{in} is the ion-neutral collision frequency.

Following Tsurutani et al. (2007), we calculate the ion-neutral coupling time, τ_{in}, for a representative altitude of ~340 km. This reference level was chosen because it is near the equatorial ionization (EIA) density peak location where the ion-neutral drag is expected to be approximately a maximum (Tsurutani et. al., 2007).We obtain ν_{in} from the expression given by Bailey andBalan (1996), i.e., $\nu_{in} = 4.45\times10^{-11}$. n_o .$T^{1/2}$.$(1.04 - 0.067 \log_{10} T)^2$, where T is average of the O and O^+ temperatures. Using O and O^+ temperatures of ~10^3 K and noon-time densities of n_o= 1.1×10^9 cm^{-3} and n_i= 3.5×10^6 cm^{-3}, we get τ_{in}~ 5 min.

Considering the initial (boundary) conditions at the reference altitude (z ~340 km) as $U = 0$ at t=0, the solution to Eq.(1) can be written as

$$U = V_d\left[1 - \exp\left(-{}^{t}/_{\tau_{in}}\right)\right] \qquad (3)$$

The uplift of the neutrals will cause changes in their density with altitude, z. To first order, the continuity equation for O can be written as:

$$\frac{\partial n}{\partial t} + U\frac{\partial n_o}{\partial z} = 0 \qquad (4)$$

On substituting U from Eq.(3) and integrating Eq.(4) with the boundary condition that n=n_o at t =0, we get the change in neutral density as:

$$\delta n = \frac{V_d}{H}\left[t - \tau_{in}\left(1 - \exp\left(-{}^{t}/_{\tau_{in}}\right)\right)\right] \qquad (5)$$

where $\delta n = (n - n_o)/n_o$, and $H = \left(\frac{1}{n_o}\frac{\partial n_o}{\partial z}\right)^{-1}$ is the oxygen neutral scale height. Equation (5) implies that neutral density time dependence at progressively higher altitude layers will be affected by the arrival of neutrals uplifted from below due to the ion-neutral drag. We must emphasize that Eq.(5) gives only the first-order estimates. Implicitly it is assumed that the pressure gradient and gravity effects balance each other during the uplift. For more accurate estimates, one has to consider the nonlinear coupling terms along with the inclusion of gravity, pressure gradients,viscosity, advection of the O-atom flow (i.e, the

U.∇U term which has been neglected in Eq. (1)), and the effects of heating and expansion during the uplift process.The decrease of the ambient oxygen density is also not taken into account in the above estimate. All of these will have to be considered in a fully self-consistent nonlinear code.

3. Satellite drag due to O^+ and O enhanced fluxes during superstorms

Drag force per unit mass on a satellite moving through the Earth's atmosphere is given by (Chopra, 1961; Gaposchkin and Coster, 1988; Moe and Moe 2005; Pardini et al., 2010; Li, 2011):

$$F = \frac{1}{2}C_D\left(\frac{A}{M}\right)(mn)V_s^2 + \frac{1}{2}C_{Di}\left(\frac{A}{M}\right)(m_i n)V_s^2 \quad (6)$$

where C_D represents the neutral drag coefficient due to impingement of O atoms on the satellite surface and C_{Di} is the ion (Coulomb) drag coefficient due to scattering of O^+ ionsby the satellitepotential (a satellite moving in an ionized atmosphereacquires an electric charge mainly through collisionswith charged particles), *m* is the mass of neutral atom (O), and m_i is the mass of O^+ ions, *A* is the satellite cross-section area perpendicular to the velocity vector, *M* the mass of the satellite, and V_s is the satellite velocity with respect to the atmosphere. The drag coefficients C_D and C_{Di} have been discussed theoretically and calculated from empirical observations of satellite deceleration and other data by many workers (Chopra, 1961; Cook, 1965, 1966; Fournier, 1970; Gaposchkin and Coster, 1988; Moe and Moe 2005; Moe et al., 1998; Pardini et al., 2010; Li, 2011). The information on the gas-surface interaction on the surface of the satellite and contamination of the satellite surface due to the absorbed atomic oxygen, are essential to accurately determine the drag coefficients (Chopra, 1961; Cook, 1965, 1966; Pardini et al., 2010). Various studies (Chopra, 1961; Cook, 1965, 1966; Pardini et al.,2010)show that for spherically- or cylindrically- shaped satellites, the neutral drag coefficient C_D varies from ~2.0 to 2.8 between altitudes of z = ~200 to 800 km with a most commonly used value of C_D=2. In contrast the Coulomb drag coefficient C_{Di}varies widely with altitude, e.g., $C_{Di} = 7\times10^{-5}$, 0.32 and 6.1 at z=250, 500 and 800 km, respectively (Chopra, 1961; Li, 2011). The area to mass ratio of the satellite, *A/M*, can have values of ~ 0.038 - 0.285 cm^2/g, which obviously varies from satellite to satellite. A typical value of a satellite payload is A/M=0.1 cm^2/g (Gaposchkin and Coster, 1988; Pardini et al., 2010), which we will use in our following calculations. A typical value for the LEO satellite speed with respect to the atmosphere is $V_s \sim 7.5$ km s^{-1}.Thus ourcalculations of n_o (O densities) during superstorms can be used to calculate the drag force on LEO satellites by using Eq. (5).

In Table 1, for the super magnetic storm of 1-2 September 1859, we give the estimates of altitude, z, reached by uplifted O atoms from the integration of Eq. (3) (column 2), change in O density from Eq. (5),δn (column 3), the Coulomb drag coefficient, C_{Di} extrapolated from the values given by Chopra (1961) and Li (2011) (column 4), and the drag force per unit mass, F calculated from Eq. (6)(column 5) for various values of time, t, after the application of 20 mV/m PPEF in the equatorial ionosphere (with a constant B_0=0.35×10^{-4} T)(column 1). A constant neutral drag coefficient C_D =2.0, V_s = 7.5 km s^{-1}, and A/M=0.1 cm^2/g and for a scale height of $H \sim 50$ km are assumed. The reference altitude is taken at z=340 km with the oxygen atom (O) mass density mn_o=2.94361×10^{-14} g cm^{-3}. The background neutral O density is assumed to decrease exponentially with altitude with a scale height of H = 50 km. It is interesting to note that in just 20 minutes (t = 1200 s), the uplifted O atoms reach an altitude of z = 856 km from the reference altitude of 340 km at t = 0. The drag force per unit mass on the satellite is F= 0.0017 cm s^{-2} at z = 340 km (t = 0) and it increases to F= 0.0692 cm s^{-2} at an altitude of z = 856 km (t = 1200 s), an increase of more than 40 times! As one can see from Column 4, the Coulomb drag coefficient increases with altitude, therefore its contribution to F increases as O^+ ions and O neutral atoms are uplifted by the action of PPEFs via the **E**×**B** force. We find that Coulomb drag dominates over the neutral drag at altitudes above ~ 750 km.

4. Conclusions

We have done preliminary estimates of the drag force per unit mass on typical low Earth orbiting satellites moving through the ionosphere during super magnetic storms, like the Carrington 1-2 September 1859 event. A simple first-order model is employed to calculate the changes in density of the neutral O atoms at different altitudes due to ion-neutral drag between the uplifted O^+ ions and O neutral atoms. The uplifted O^+ ion speeds result from the **E**×**B** force from the PPEFs. It should be noted that there is no expansion of the column of gas from 340 km to 850 km, rather the entire column of atmosphere is uplifted by the **E×B** force. There may be a slight increase in the temperature of the O atoms due to the friction with O^+ ions. Consequently, as the pressure remains the same or is slightly increased, it will more or less balance the gravity during the first 20 minutes or so. Eventually, the nonlinear coupling, gravity, pressure gradients, advection of the O-atom flow arising from divergence terms, and viscosity effects will dominate and will stop the uplift of the neutrals. Therefore, this simple model may be reasonable for the first ~ 20 minutes after the onset of the PPEF in the ionosphere.

We may point out that the nightside ionosphere may be depressed due to change of sign of **E×B** drift (i.e., downward drift instead of uplift). However, as the neutral O atom density will increase sharply at lower altitudes, the relative change in O atom density due to ion-neutral drag force would be relatively small, and that too limited to altitudes lower than the reference level. Since at the higher altitudes, the neutral O density is expected to remain more or less unchanged, the satellite on the night side will not feel any extra drag force due to **E×B** drift. Therefore, we do not expect that the nightside ionosphere can compensate for the extra dayside satellite drag due to uplifted O atom over a satellite orbit.

In this paper, we have not considered the effect of Joule heating in increasing the neutral densities and temperatures during super magnetic storms. The Joule heating occurs in the auroral regions, but it may come down to lower latitudes during superstorms. Therefore, the effects due to Joule heating are important primarily at high latitudes initially, and such increases are expected to manifest at equatorial latitudes after 2-3 hours or more. However our mechanism will occur near the equator and at middle latitudes. At middle latitudes the two mechanisms would most likely merge. Furthermore, it can be estimated that an increase in neutrals temperature of 200 K, say from 800 to 1000 K, will cause a factor of 10 increase in the O density at 850 km just by the scale height effect. A 400 degree increase in temperature would increase the O density by a factor of 100 at 850 km. This is the same increase that is obtained from our proposed mechanism. It should be remembered that the process of uplift of neutral O atoms due to penetration electric fields during super magnetic storms occurs during the span of 20 minutes.In reality, an increase in the temperature of neutrals by 200 K to 400 K in 20 minutes at equatorial latitudes by the Joule heating or any other process during magnetic storms has not been observed.

It is shown that in just ~20 minutes after the action of a 20 mV/m PPEF in the equatorial ionosphere, the neutral O atoms (and also O^+ ions) are uplifted to an altitude of z=856 km from a reference level of z=340 km. A typical spherically- or cylindrically- shaped satellite moving through the ionosphere at altitudes of ~ 850 km would experience a 40 times more drag per unit massthan normal. If larger IEFs associated with either superflares (see Maehara et al., 2012, Tsurutani and Lakhina, 2014) or during extreme magnetic storms stronger than the Carrington storm (Vasyliunas, 2011, Lakhina and Tsurutani, 2016), are imposed on the magnetosphere then larger scale PPEFs will be imposed on the dayside ionosphere with even greater O atom uplift. We do not know when such cases can occur at the Earth, but we cannot exclude the possibility at this time.

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Table 1: Estimates of the altitude, z, attained by uplifted O atoms, relative change in O density, δn, Coulomb drag coefficient (extrapolated from Chopra (1961) and Li (2011)), C_{Di}, drag force per unit mass on satellite, *F*, at different times, t, after the onset of a PPEF of 20 mV/m in a Carrington (1-2 September 1859) type super magnetic storm. The reference altitude is taken at z=340 km with the Earth's magnetic field, $B_0=0.35\times10^{-4}$ T, and the oxygen atom (O) mass density $mn_o=2.94361\times10^{-14}$ g cm^{-3}. The background neutral O density is assumed to decrease exponentially with altitude with a scale height of H = 50 km. The other parameters are: neutral drag coefficient C_D = 2.0, V_s = 7.5 km s^{-1}, and area to mass ratio of satellite, A/M=0.1 cm^2/g, and the scale height, H = 50 km.

t = time after onset of PPEFs, in s	z = altitude attained, in km	δn = change in O density	C_{Di} = Coulomb drag coefficient	*F*= drag force per unit mass, in cm s^{-2}
0	340	0	0.01	0.0017
300	402	1.26	0.15	0.0028
600	534	3.88	0.32	0.0075
900	690	7.01	1.43	0.0199
1200	856	10.32	6.1	0.0692