Response to comments by the Referees on the manuscript npg-2017-33 entitled,“Satellite drag effects dueto uplifted oxygen neutrals during super magneticstorms” by Gurbax S. Lakhina and Bruce T.Tsurutani

We thank the Referees for carefully reading the manuscript, and for their very useful comments. We have revised the paper in light of their comments. In our point-to-point Reply below, the comments by the Referees are shown in regular fonts, and our reply in *Italic* fonts.

Anonymous Referee #1 (RC1)
Comment:
I have examined the manuscript npg-2017-33 submitted by Gurbax S. Lakhina and Bruce T. Tsurutani entitled "Satellite drag effects due to uplifted oxygen neutrals during super magnetic storms". This paper identifies basic aspects of plasma behavior that have not been previously considered in calculations of satellite drag. The work is creative, based on solid principles, and makes definitive quantitative predictions of relevance to space scientists. I recommend the paper for publication in its present form.

Reply: Thank you very much for your encouraging comments and recommending the paper for publication.

Y. Narita (Referee#2)(RC2)

Comment:

The manuscript develops a simplified model for the oxygen uplift from the low-altitude ionosphere to the higher altitude caused by the enhanced E x B drift effect during the extreme or major geomagnetic storm time, and applies the oxygen fluxes to predicting the satellite drag by taking the Carrington super-magnetic storm event as an example. The manuscript is a beautiful application involving the space science (the Sun-Earth relation), the physics of the ionosphere, and the engineering aspect (satellite drag estimate). The model for the oxygen uplift (section 2) is rather simple, but nevertheless contains the essence of the physical process (uplift flow estimate, drag force between plasma and neutral, scale height, and continuity). The model is developed for the linear treatment of the uplift, but the authors address what effects need to be considered when upgrading into the nonlinear treatment.
The authors apply the oxygen density profile (from section 2) to the model of the satellite drag force (Equation 6, section 3), and find that the drag force can significantly vary from a lower to a higher altitude by a factor of about 40. The authors also find that the electrostatic drag force (Coulomb effect) dominates over that of the neutral gas at higher altitudes above 750 km.
The manuscript reads well. The logic and the calculations are easy to follow. And the study is concise with a clear message to the audience. The manuscript will also serve as a beautiful example of writing a paper for the young students. I enjoyed reading the manuscript. I have only minor comments in a hope of improving the quality of the manuscript a bit (the authors may disagree). In any case, I recommend the manuscript for a prompt publication.

Reply: We thank the referee for going through the manuscript critically and recommending it for publications. We have taken all your suggestions into account in the revised manuscript.

Comment:
page 2, line 37. "GPS" appears for the first time in the main text. I propose to rewrite into "GPS (Global Positioning System)" such that the readers can continue reading the paper without being disturbed by the acronym.

Reply: Done. Thank you.

Comment:
page 4, line 91. I wonder how the reference altitude (340 km) was chosen. Can the authors say if it is conventional or maybe if it is from a computational reason?

Reply:Thank you for raising this issue. For the calculations, the reference level at 340 km was chosen because it is near the equatorial ionization anomaly (EIA) density peak location where the ion-neutral drag is expected to be approximately a maximum (Tsurutani et. al., 2007). This is included in the text now.

Comment:
page 4, line 107 to page 5, line 109. Should the advection of the O-atom flow (U dot nabla U) be included for the nonlinear treatment, too? Turbulence physicists might find the advection term as interesting as the other effects.

Reply:Good suggestion. Done. Thank you.

Comment:
page 5, line 127. "adsorbed" should read "absorbed".

Reply: done. Thank you.

Comment:
page 6, line 140. As a reader, I prefer to see "we give the estimates of..." rather than "we have given the estimates..." because the discussion sounds on-going. But the authors can decide.

Reply: Done. Thank you.

Comment:
page 6, line 164. It is better to write "EXB" as nmathbf{E} ntimes nmathbf{B} coherently in the text.

Reply: Done. Thank you.

Anonymous Referee #3 (RC3)

Received and published: 14 September 2017

This paper addressed on uplifted oxygen neutrals due to the prompt penetrating electric fields in the dayside ionosphere, and discussed the drag force on a low Earth orbiting satellite during super magnetic storms, like the Carrington superstorm. The physical process of the uplifted oxygen ions and atoms was concisely documented, and the satellite drag force was reasonably estimated.

Reply: We thank the referee for going through the manuscript critically and for the encouraging comments.

Comment:

However, I wonder if the ionosphericatmosphere in the night side may be depressed during the penetration of electric field,and then the drag force may be reduced in the night side. Therefore, the drag force averaging one orbiting cycle may be compensated in some sense.

Reply: Yes, we agree that the nightside ionosphere will be depressed due to change of sign of $\boldsymbol{E}\times\boldsymbol{B}$ *drift (i.e., downward drift instead of uplift).This was mentioned in the Tsurutani et al. 2004 discovery paper. 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 at 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 nightside will not feel any extra drag force due to* $\boldsymbol{E}\times\boldsymbol{B}$ *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. This point is addressed by adding an extra text on page 7 in the revised manuscript.*

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

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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~~more~~ 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 & 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-directed neutral 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, 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:

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

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 and Balan (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 $n_o = 1.1\times10^9$ cm^{-3} and $n_i = 3.5\times10^6$ cm^{-3}, we get $\tau_{in} \sim 5$ 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 densities are 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):

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

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^+ ions by the satellite potential (a satellite moving in an ionized atmosphere acquires an electric charge mainly through collisions with 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~~adsorbed~~ 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 our calculations 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~~we have given 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 $B_0=0.35\times10^{-4}$ 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 $mn_o= 2.94361\times10^{-14}$ g cm^{-3}.The background neutral O density is assumed to decrease exponentially with altitude with a scale height of H=50 km. 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 $\mathbf{E}\times\mathbf{B}$ 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**~~EXB~~ 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) 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