51 st ESLAB Symposium: Extreme Habitable Worlds, 4-8 Dec. 2017

Effects of space weather on the ionosphere and LEO satellites' orbital trajectory in equatorial, low and middle latitude

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Contents

Main study Objective and scope

We study the effects of space weather on the ionosphere and LEO Satellite orbital trajectory from equatorial to mid-latitude regions, with focus or reference to the super-storms of October/November 2003 and the surrounding period (15 October - 14 November 2003).

- Brief review of space weather effects on the ionosphere and thermosphere

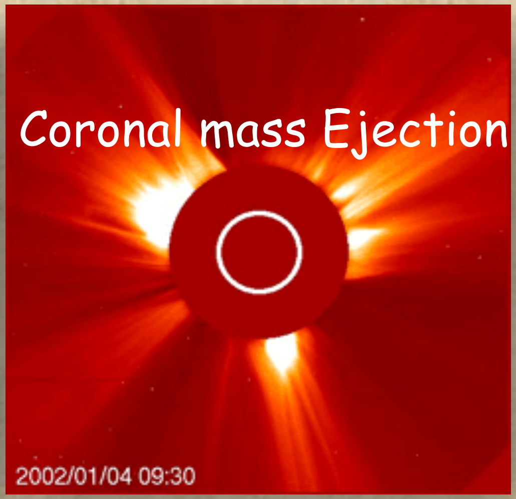
- Simulate the trend in variation of satellite's orbital radius (r), mean height (h) and orbit decay rate (ODR) at 450 km in the middle (60°), Low (30°) and equatorial (0°) latitudes.

- analyse the density (ρ) and temperature (T) of the thermosphere - atmospheric drag force on LEOSs and consequent orbital decay strongly depends on the state of the atmosphere (defined by ρ and T)

Introduction

Space weather refers to the dynamic, variable conditions in the coupled space environment, including conditions on the sun and terrestrial atmosphere, that can affect the performance and reliability of space-bone and ground-based technological systems, as well as directly or indirectly endanger human life.

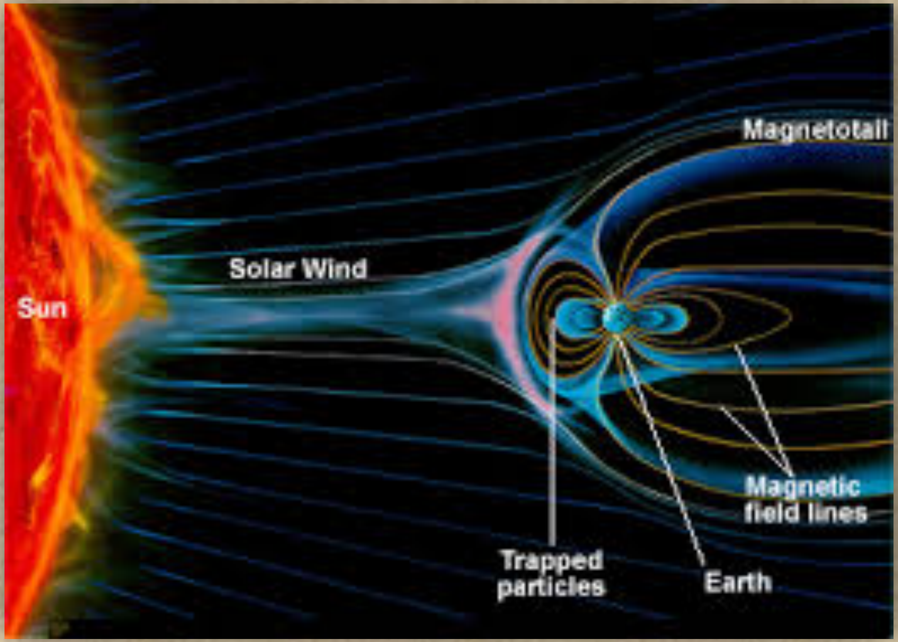
Space weather conditions are caused by the variability of solar activity (e.g., solar wind streams (mainly HSS and CIR), prominence eruption, coronal mass ejections (CMEs), solar flares etc.) via associated high-energy charged particles and electromagnetic (EM) radiation.

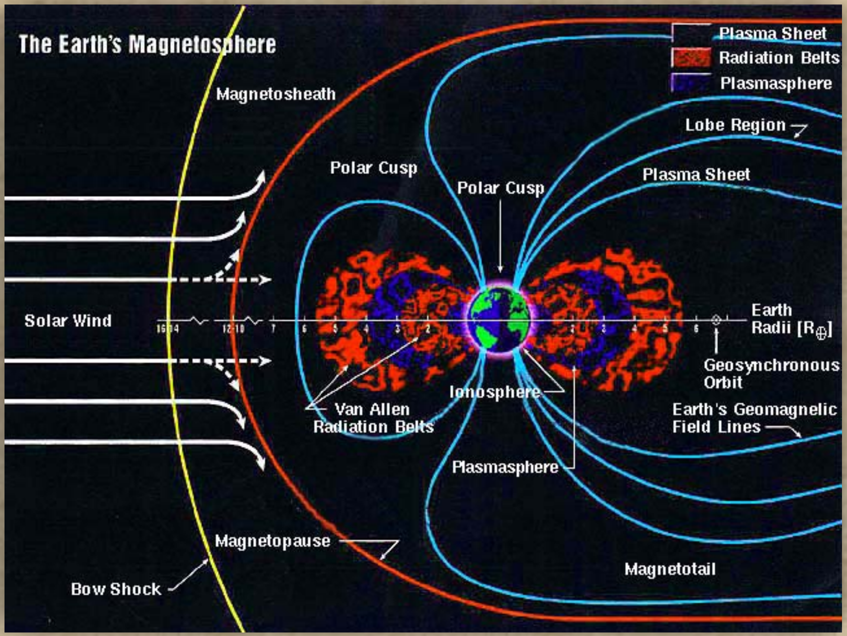


Courtesy: NASA

Introduction continued…

Bulk of space weather effects are triggered by interaction of accelerated solar energetic particles and EM radiations with the Earth's magnetic field.





Such interaction causes momentary depression (instability) of the magnetosphere leading to other geo-effective inter-related Phenomena e.g.,

- Shock waves
- solar particle precipitation events
- interplanetary magnetic field (IMF) variations
- geomagnetic storms and magnetospheric substorms etc.

Introduction continued…

Geomagnetic storms are the leading driver of the large-scale coupled magnetosphere-ionosphere instability in the geospace environment.

Geomagnetic storms result from variations in the solar wind during 2 main processes

- High speed solar wind (HSS) & stream-stream interaction (creating CIR)
- Coronal mass ejections (CMEs) – most geo-effective!!!

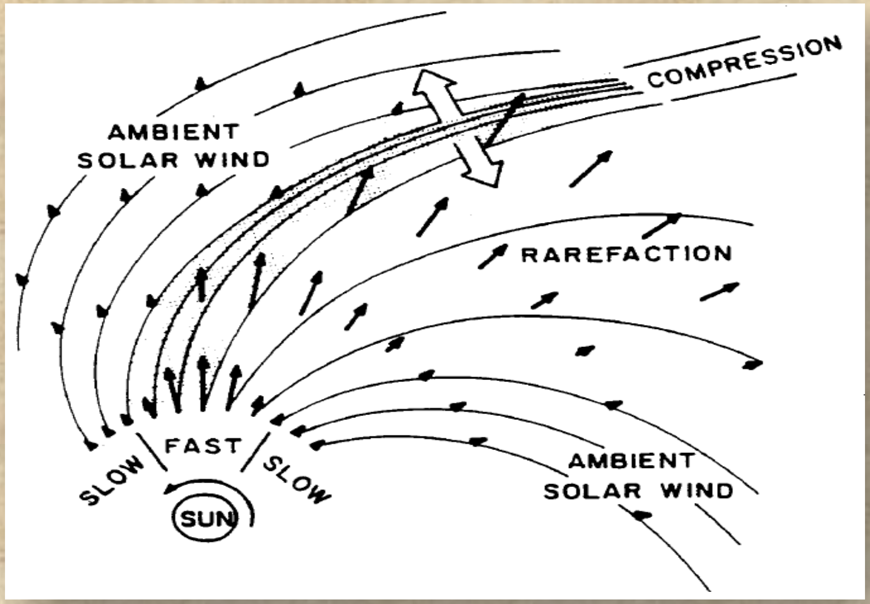


Fig: fast and slow solar wind Stream-stream interaction leading to formation corotationg interaction region (CIR) in solar wind

Solar wind conditions that are effective for producing geomagnetic storms are;

- sustained (several to many hours) periods of high-speed solar wind, and
- a southward directed solar wind magnetic field at the dayside of the magnetosphere

Introduction continued…

Some effects of space weather on the atmosphere, space-bone & ground-based technology include:

- heating and expansion of the atmosphere (ionosphere & thermosphere)
- driving intense currents in the magnetosphere & ionosphere (including GIC)
- modification of thermospheric and ionospheric parameters;
  - atmospheric density distribution,
  - total electron content (TEC),
  - ionization rates, and conductivity gradient and reference height of the ionosphere
- accelerated orbital decay of LEO Satellites due to solar induced increase in atmospheric drag
- degradation of satellite's sensor, solar array and critical components
- modification of radio signal paths
- hampering precision of GPS measurement
- GIC-induced disruption and damage of modern electric power grids
- GIC-induced corrosion of oil/gas pipelines etc.

Time- and latitude-dependence of space weather induced ionospheric responses

The structures of the ionosphere and thermosphere (and solar-forcing-induced effects on the regions) vary significantly **with time** (e.g., solar cycle, seasonal, diurnal) and **location or latitude** (e.g., high-, mid- or low-latitude, equatorial, polar regions, auroral zone).

- Space weather effects are more severe in high latitude.
- In the mid latitude, the effects are mainly an after- or delayed-response
- minutely observed (and sometimes not detectable) in low latitude and equatorial region.

However, there are other solar-driven phenomena that significantly impact low latitude and equatorial regions.

- Intervals HSS and CIR causes high variability in values of daytime vertical total electron content (VTEC) in low- and mid-latitude (Verkhoglyadova et al., 2013).
- High-intensity, long-duration continuous auroral electrojet activity events (HILDCAAs) drives prompt response of equatorial ionosphere and continuous penetration of planetary electric field (Wei et al., 2008; Koga et al., 2011; Tsurutani et al., 2011).
- GIC activity is also enhanced at the equator during severe geomagnetic storms (Alken and Maus, 2007; Carter et al., 2015)

Features of geomagnetic storms of October/November 2003

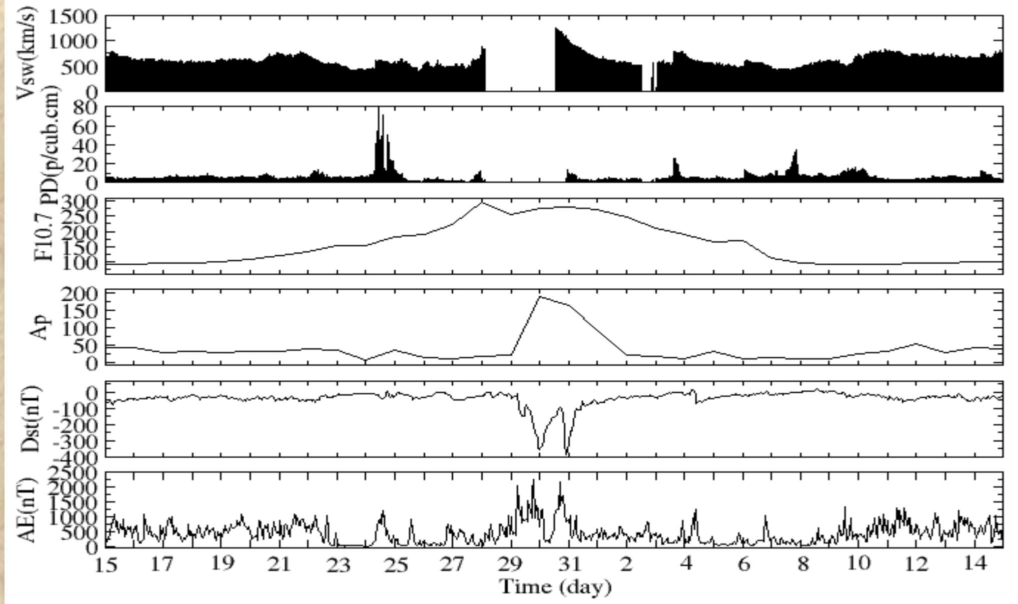


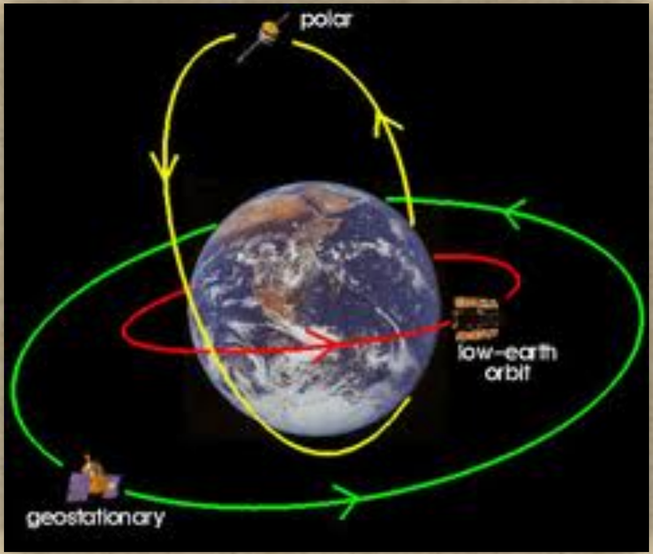
Fig. Variation in solar wind speed (Vsw) and associated particle density (PD), solar radio flux (F10.7), geomagnetic Ap, disturbance storm time Dst index and auroral electrojet (AE) during 15 October - 14 November 2003.

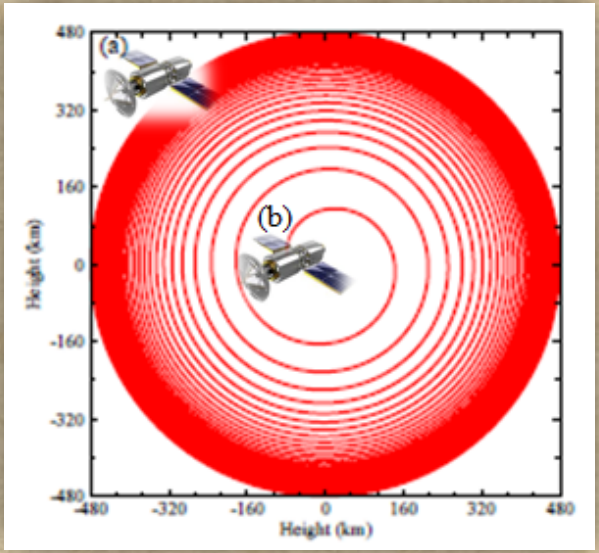
Solar and geomagnetic activity were unprecedented during the interval - The events between 26 October and 1 November are important and of particular interest.

- peak of 298 in F10.7 value on 27/28 October, and 189 in Ap on 29 October
- with associated recurrent storms on 28th, 29th and 30th October (Dst up to -383).
- The AE values also fluctuated significantly with peak up to 2241 (nT) during 28-30 October
- Less-intense storms with Dst between -50 and -69 also occurred at intervals during the entire period
- About 4 geo-effective halo CMEs were recorded between 26 October and 4 November (with speed up to 2000+ km/s), and associated X1, X17, X1/M2 and X28 flares on 26th, 28th Oct., 3rd and 4th Nov.
- Comparatively, 2-3 flares during the period were outstanding and classified as the most powerful flare recorded since 1976 (Plunkett, 2005; Vats, 2005).

Effects of space weather-induced thermospheric perturbation and heating on the orbital trajectories of LEO satellites

Atmospheric drag is the strongest force perturbing the motion of LEOSs. Nominal drag on LEOSs is usually enhanced by solar forcing induced variations in thermospheric T and ρ.





- Atmospheric drag increases the risk of spacecraft collision due to the increased margins of error in spacecraft positioning (e.g. the 2009 Iridium-Cosmos collision)
- resulting in significant uncertainties in the re-entry location of de-orbiting spacecraft (e.g. the UARS and ROSAT re-entries in 2011).
- constantly takes energy away from the orbit - gradually decreases the semi-major axis and period of LEOSs, but increases the velocity components of the satellite as it spirals inward

Variation in satellite's orbital radius, mean height and orbit decay rate due to response of thermospheric T and ρ

The general equation of motion for a satellite moving under the attraction of a point mass planet with perturbations effect (e.g., gravitational or non-gravitation forces) is given by the equation (Chobotov, 2002),

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{GM\mathbf{r}}{r^3} + a_p,$$

where, **r** is the position vector of the satellite, *G* is the gravitational const., *M* is the mass of the Earth, a_p is the resultant vector of all perturbing accelerations.

The equation of drag force (or acceleration) is given by (King-Hele, 1987; Wertz and Larson, 1999; Chobotov, 2002; Xu et al., 2011),

$$F_d = -\frac{a_d}{m_s} = -\frac{1}{2}\rho A_s C_d V_s^2,$$

where, V_s is the velocity of the satellite with respect to the atmosphere, A_s is the satellite effective (projected) area, ρ is atmospheric density, m_s is the mass of the satellite and C_d is the dimensionless drag coefficient of the satellite.

The change in the radius of the satellite in near circular orbit per revolution is given by (Wertz and Larson, 1999; Chobotov, 2002; Xu et al., 2011).

$$\Delta r = -2\pi(\frac{AC_d}{m})\rho r^2,$$

Analysis of drag force on LEO satellites

The differential equation for the mean radius per revolution (mrpr) is given by,

$$\frac{dr}{dt}(mrpr) = -\rho\frac{C_d A}{m}\sqrt{GMr}$$

To get the instantaneous velocity and position of the satellite we formulated and solved a set of coupled diff. Eqns. in spherical polar co-ordinate system (*r, θ, Ø*),

$$\dot{v_r} = -\phi r^2 (A_s C_d/m_s),$$

$$\dot{r} = v_r,$$

$$\ddot{\phi} = -\frac{1}{2} r \rho \dot{\phi}^2 \frac{A_s C_d}{m_s},$$

$$\dot{\phi} = v_\phi / r,$$

where, v_r and $v_Ø$=radial & tangential vel. Components

The extent of drag on a satellite depends on its orbit, injected height, ballistic coefficient ($A_s.C_d/m_s$) and atmospheric density profile through which the satellite traverses.

ρ is computed using the NRLMSISE-00* empirical atmospheric model as a function of time, location, solar activity and geomagnetic activity.

*Naval Research Laboratory MSIS (Mass Spectrometry and Incoherent Scatter) Extended

Analysis…continued

Solar radio flux (F10.7) - represent indirect measure of upper atmosphere heating by solar energetic particles and extreme ultra-violet (EUV) radiation.

The moving average of F10.7 over three solar rotations (about 81 days) - represents a slowly varying component of solar rotation

The geomagnetic planetary Ap index - represents the measure of additional atmospheric heating that occurs during magnetic storms.

Aerodynamic drag force effect was computed for a hypothetical LEO satellite:
with h = 450 km
m = 1100 kg
A = 1.1 sqm
Cd = 3.7

Results and Discussion

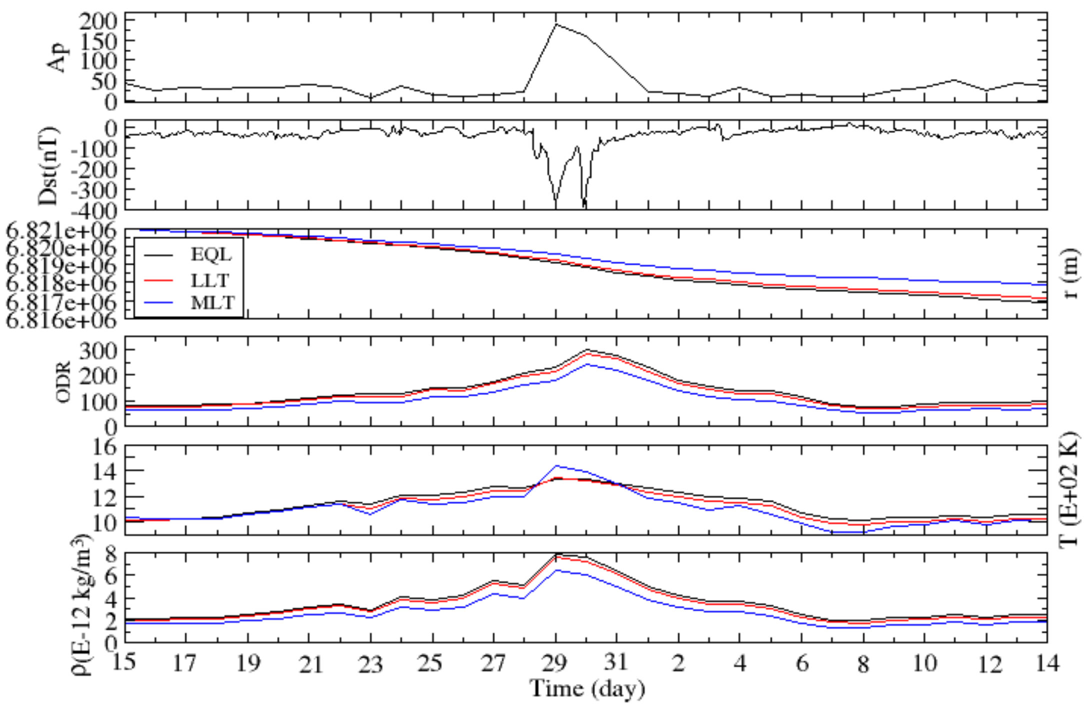


Fig. Daily mean variations in Ap and Dst values, thermospheric temperature (T) and density (ρ), and the satellite's orbital radius (r), mean height (h) and orbit decay-rate (ODR) in equatorial region (EQL), low latitude (LLT) and mid-latitude (MLT) during 15 October - 14 November 2003.

- The peak of the parameters occurred during 29-30 October, and concurrent with the peaks of the recurrent geomagnetic storms.
- T peaked at the MLT, but maintained about the same value at EQL and LLT.
- The rise in T in MLT (compared to EQL and LLT) during 29-30 October is due to storm-induced joule heating.
- The total decay in r in EQL, LLT and MLT is about 4162 m (4.16 km), 3885 m (3.89 km) and 3177 m (3.18 km) respectively.
- The ODR also varied with latitude - the observed maximum ODR associated with the storms on 29th and 30th October 299 m/day and 277 m/day in EQL, 285 m/day and 263 m/day in LLT, and 241 m/day and 220 m/day in MLT.

Results…continued

Nominal aerodynamic drag on LEOSs is usually enhanced by space weather condition. To investigate space weather influence on LEOS nominal aerodynamic drag we simulate the trend in variation of r or h and ODR with and without control on the solar parameters in 3 regimes viz.

(i) excluding solar indices or effect where h=h0 and ODR=ODR0
(ii) with mean values of solar indices for the interval where h=hm and ODR=ODRm and
(iii) with actual daily values of solar indices (h and ODR) for the interval.

Results…nominal vs solar-induced effect

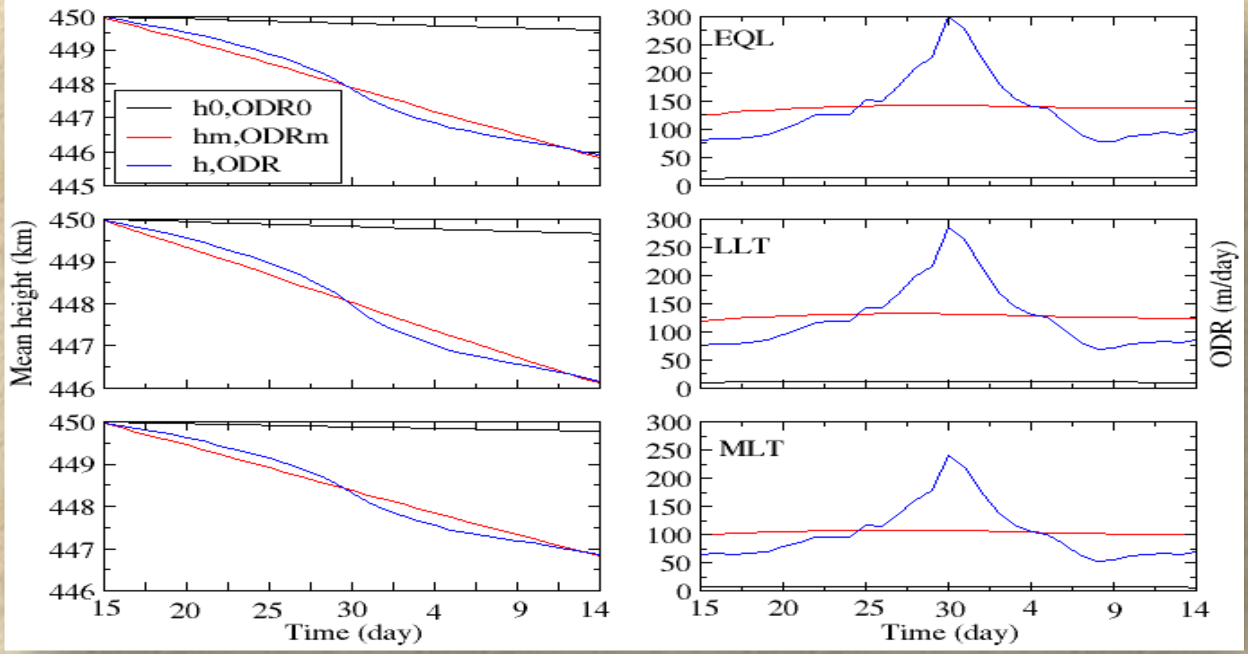


Fig. Daily variation in h0 and ODR0 (excluding solar effect), hm and ODRm (with mean values of solar indices) and h and ODR (with actual daily values of solar indices) in EQL, LLT and MLT during 15 October - 14 November 2003.

- h0 and hm are respectively 0.40 km and 4.20 km in the EQL, 0.34 km and 3.89 km in LLT, and 0.22 km and 3.17 km in MLT - corresponds to solar or space weather induced orbit decay (hm-h0) of 3.8 km, 3.55 km and 2.95 km, respectively.
- values of ODR0 and ODRm are 13.50 and 137.80 in EQL, 11.20 and 128.10 in LLT, and 7.20 and 104.5 in MLT - corresponds to respective solar-induced orbit decay-rate (ODRm-ODR0) of about 124.30 m/day, 116.90 m/day and 97.30 m/day.
- Computation with actual daily values of solar parameters during the peak of the storm produced a resultant ODR of about 299 m/day, 285 m/day and 242 m/day in EQL, LLT and MLT respectively - correspond to additional ODR (with respect to daily mean value) of 161 m/day, 117 m/day and 137 m/day.
- This implies that severe geomagnetic storms of that magnitude can cause additional ODR increase of about 117%.

Results…continued

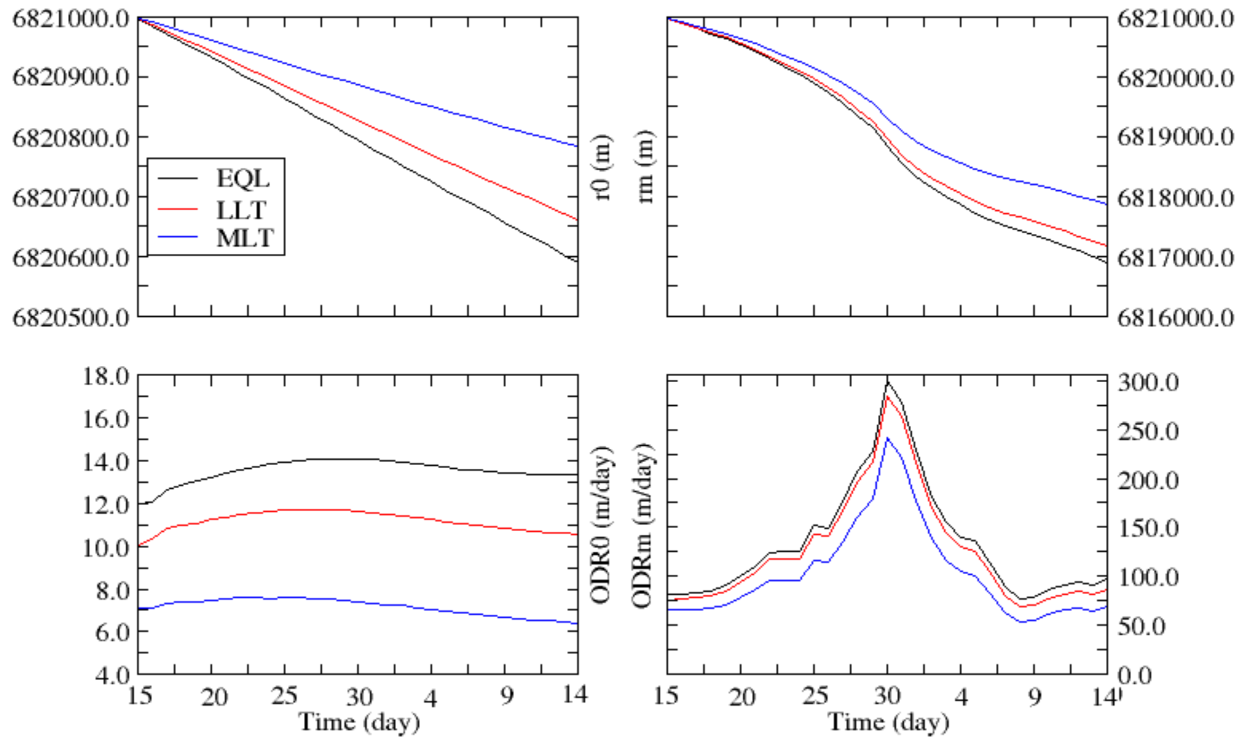


Fig. Variation in r0, r, ODR0, and ODR in EQL, LLT and MLT during 15 October - 14 November 2003.

- The simulated values of r0 and rm are 410.64 and 4183.99 m in the EQL, 339.14 and 3832.53 m in the LLT, and 216.75 and 3134.56 m in the MLT.
- The trend in variation of all the parameters (including ODR0 and ODRm) are consistent with those of h components in earlier analysis.
- The usual symmetry in ODR0 (left bottom panels) is severely distorted under strong solar and geomagnetic influence.
- The storm induced accelerated decay (rm) around 29-30 October reflected as a notable spike in ODRm during the time

CONCLUSION

- The structures of the ionosphere and thermosphere (and solar-forcing-induced effects on the regions) vary significantly with time (e.g., solar cycle, seasonal, diurnal) and location or latitude (e.g., high-, mid- or low-latitude, equatorial, polar regions, auroral zone)

- The total decay in orbital radius r of the LEO satellite at h=450 km in EQL, LLT and MLT during the entire period is about 4162 m (4.2 km), 3885 m (3.9 km) and 3177 m (3.2 km) respectively - the nominal decay (r=r0) is 0.4 km, 0.34 km and 0.22 km, while solar-induced orbital decay (r=rm) is about 3.8 km, 3.55 km and 2.95 km respectively.

- The respective nominal orbit decay rate (ODR0) is about 13.5 m/day, 11.2 m/day and 7.2 m/day, while solar-induced ODRm is about 124.3 m/day, 116.9 m/day and 97.3 m/day.

- severe geomagnetic storms of this magnitude can cause additional ODR increase of about 117% (from daily mean value).

- The extent of space weather effect on LEOSs trajectory, however, significantly depend on the ballistic co-efficient and orbit of the satellite, phase of solar cycles, intensity and duration of driving solar event.

References

Nwankwo V.U.J., Chakrabarti S.K. and Weigel R.S. (2015), Effects of Plasma Drag on Low Earth Orbiting Satellites due to Solar Forcing Induced Perturbations and Heating. ASR, **56**, 47-56

Nwankwo V.U.J. and Chakrabarti S.K. (2015), Analysis of Planetary and Solar induced Perturbations on Trans-Martian Trajectory of Mars Missions before and after Mars Orbit Insertion. INJP, **89**, 1235-1245

Nwankwo V.U.J. and Chakrabarti S. K. (2014), Theoretical Modeling of Drag Force Impact on a Model International Space Station Satellite during Variation of Solar Activity. TJSAS, **12**, 47-57

Acknowledgement

- The World Academy of Science (TWAS), ICTP, Trieste, Italy Postgraduate/Research Fellowship during which this work was done.
- Anchor University Lagos for partial travel support.

Thank You