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The Scientific Basis for Solar-Terrestrial Predictions at National Physical laboratory, New Delhi

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ABSTRACT

Solar-Terrestrial Predictions are essential to plan a variety of systems including communication and navigation, Earth-orbiting satellites and other space missions. The paper describes the prediction services provided by the National Physical Laboratory, New Delhi, which incidentally is the only source in India for such predictions. The paper also gives examples of some innovative approaches introduced to improve the prediction accuracy such as Equatorial Electrojet strength as an index in ionospheric predictions. The recent controversies regarding the contribution of natural solar variability vis-à-vis anthropogenic sources in the global/climate change have also enhanced the interest of the Geophysical community in fine-tuning Solar-Terrestrial Predictions.

INTRODUCTION

National Physical Laboratory, New Delhi operates Indian RWC (Regional Warning Center) as a part of International Space Environmental Services (ISES) chain and is responsible for collection and dissemination of a wide variety of near-real-time and recent data on solar geophysical conditions to various users in India and neighbouring countries. In addition, the center is also responsible for providing forecasts on solar geophysical conditions based on the data collected from other centers located around the globe and also other observatories with in India. RWC (Boulder,USA) and RWC(Sydney, Australia) are two major sources of near-real-time data and provide a variety of observational information which includes, detailed reports on solar active regions, solar flares, solar wind, magnetic activity, Coronal Holes, Coronal Mass Ejections (CMEs), X-ray events, Radio bursts, Proton events etc.

The solar and geomagnetic phenomena driven by the sun are global in nature and deals with the inputs of different solar energy components at different altitudes. However, many critical effects of these events are region specific and we in India have to make our own forecasts for the Indian and neighborhood territories. As India hosts not merely the tropical region but also the geomagnetic ionization anomaly, the specificity of the region should be recognized and should take care of such features as the large horizontal ionization gradients and day-to day variability in prediction of ionospheric parameters. The main focus of this paper would be to review the scientific basis for solar and ionospheric predictions at National Physical Laboratory (NPL) and give some examples of the results obtained with prediction application. NPL is formally designated as center for archiving solar geophysical data. Most of this data has been digitized and used for the last 35 years in the analysis and interpretation of solar geophysical phenomena as described in the paper.

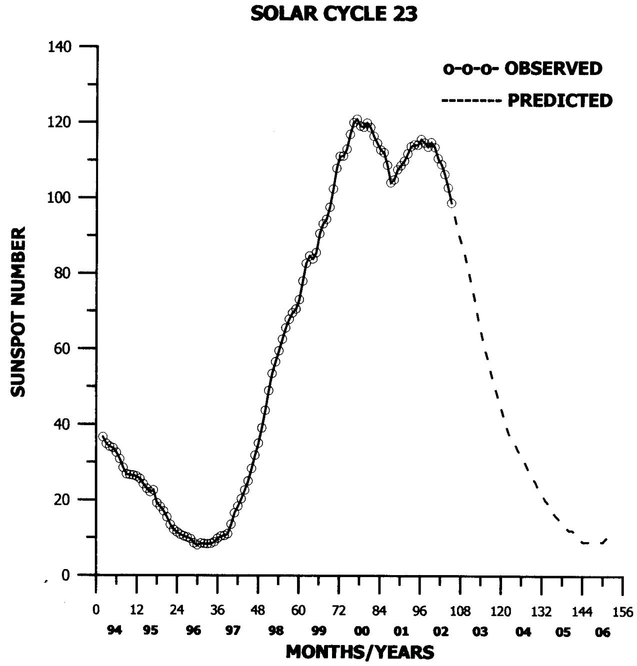

Figure 1. Sunspot Cycle 23 – Observed and Predicted.

LONG TERM SOLAR ACTIVITY PREDICTIONS

The growing dependence of human activities on sophisticated space technology makes us more vulnerable to the so called space weather disturbances which include solar events and their consequences such as magnetic storms etc. But even the less spectacular cyclic change in solar activity, best exemplified by the well known 11-year cycle is very important to understand and predict. An important activity at NPL traditionally has been prediction of sunspot cycle since early 1950s (see Fig.1 for solar cycle number 23). The 6-months-in-advance sunspot predictions are being provided to a number of user organizations including Defence, Para military and civilian agencies. Solar activity predictions are also being used by Indian Space Research Organization for optimization of orbital parameters of Low Earth Orbiting (LEO) satellites.

The long term prediction of solar activity at National Physical Laboratory (NPL) is made several months to several years in advance to aid in the following major applications:

i. Planning of orbital parameters for Low Earth Orbiting satellites, specially used for remote sensing and Defence applications.
ii. HF link and broadcast frequency allocations
iii. Trans-ionospheric propagation frequencies are constrained by ionospheric irregularities. The occurrence of these irregularities depend upon the solar activity levels.
iv. To optimize adequate robustness of satellite payloads to meet the expected particle effects during their orbital life times.

There are two main approaches (Reddy & Lakshmi 1990; Reddy et al. 1979) tried at NPL, New Delhi with certain degree of success. One approach is based on a variety of statistical techniques with an implicit assumption that the time series of past cycles is characterized by internal structures that may repeat. These cycles include the Gleissberg cycle (~90 years) and the 22-year Hale cycle. The second major approach is based on the geomagnetic observations as proxy data for the solar polar magnetic fields and using the precursors in the declining phase of the previous cycle. This uses the dynamo theory which assumes that the poloidal magnetic fields of the sun yield to a toroidal field during the declining phase of a cycle up to a critical point (solar minimum) and then generates the new cycle (Brown 1990).

Realizing the need for a real ionizing radiation index rather than a proxy index such as sunspot number or 10.7 cm flux, the group at NPL took up for the first time in the world the possibility of using existing satellite data on EUV for prediction of ionospheric parameters (Lakshmi, Reddy & Dabas 1988). The scientific basis for such an index is obvious, but the data available at that time was good only for a demonstrative exercise and not for a model for routine applications. With the multiplicity of space applications on the rise, it may now be necessary to promote a variety of solar indices to suit a particular requirement.

LONG TERM IONOSPHERIC PREDICTIONS

Until the advent of satellite communication in 1980s the only option available for long distance communication was through ionosphere-reflected communications in HF band (3-30 MHz). The HF even in the present era of modern communications is still widely used both in Defence as well as in Civilian application;

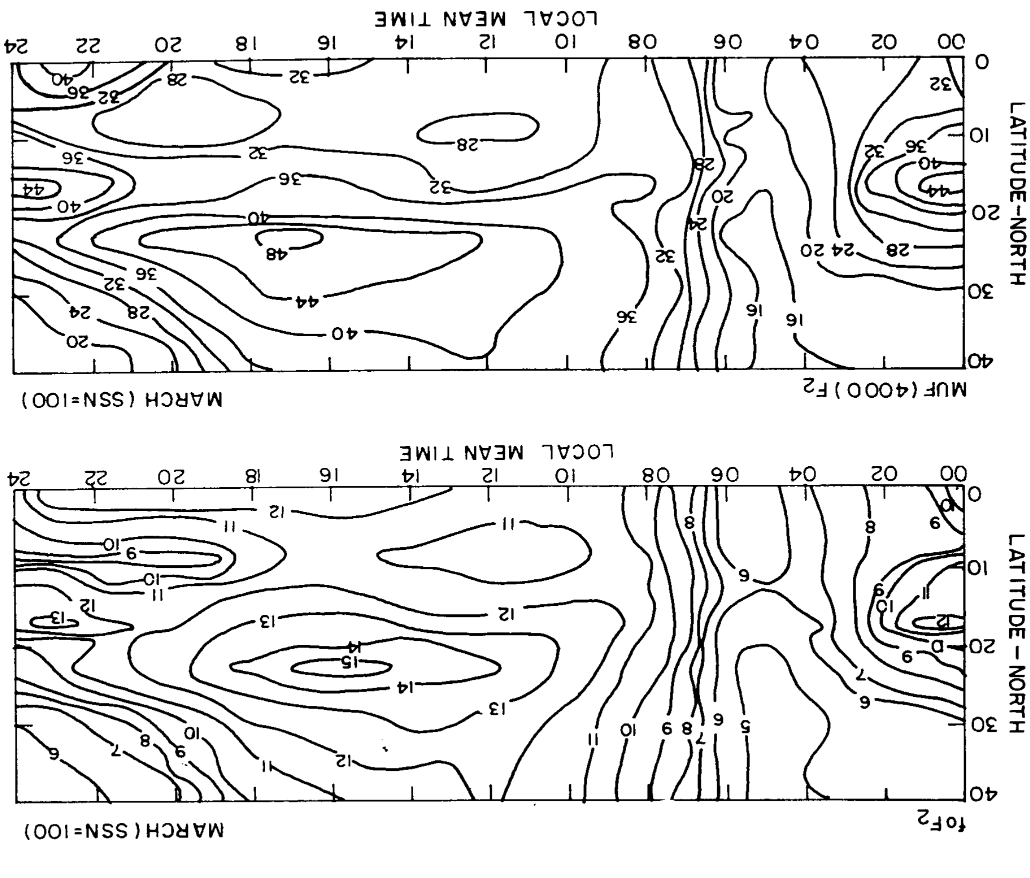

Figure 2. Contour maps of foF$_2$ and MUF (4000) F$_2$ for March (SSN 100)(after Aggarwal and Shastri, 1991).

mainly because of several natural advantages it offers including its cost effectiveness.

It is the free electrons in the ionized layers in our upper atmosphere that are responsible for reflecting the HF radio waves and carry the radio signals to far away distances on the globe. While ionospheric F layer (250-450 Km) can support radio frequencies for communication upto 4000 Km in a single reflection, the E layer (90-120 Km) can carry upto distances of 2000 Km. The ionosphere exhibits marked variations with hour of the day, season of the year, latitude and solar activity and these variations need to be predicted in advance to aid in frequency planning for HF radio systems used in point-to-point links, HF Broadcast services, OTH radars, etc. NPL, New Delhi has been providing since 1950s, long term ionospheric predictions to a number of Defence and Civilian Organizations in our country to aid in their HF communication planning.

The existence of an excellent correlation between ionospheric communication parameters (Critical frequency and peak heights) and 12 months smoothed sunspot number (R_{12}) is a well established relationship and is the main basis for any ionospheric prediction technique. NPL using a large volume of ionospheric data covering a period of more than 40 years obtained from ionosonde measurements has developed ionospheric prediction models for the Indian region (Reddy et al. 1985; Reddy et al. 1979).

The Atlas of ionospheric communication parameters over the Indian subcontinent brought out by NPL (Aggarwal & Shastri 1991) presents two cardinal HF Communication parameters namely F-region Critical frequency (f_oF_2) and MUF(4000)F_2 (Maximum usable Frequency for 4000 Km range) separately in the form of contour maps for each of the calendar months for different solar activity levels for all the 24 hours. Contour maps for the month of March for high solar activity conditions are shown in Fig.2. Using these maps frequency planning can be made for any HF radio system. The Atlas also gives the various statistical relationships between f_oF_2, M(3000)F_2 and R_{12} which can be readily used in computerized prediction procedures. NPL also has developed a computer program for total HF link parameterization including operational frequencies for different modes of propagation, circuit reliabilities etc. (Lakshmi et al. 1987)

IONOSPHERIC DAY-TO-DAY VARIABILITY

Several research studies have been conducted at NPL with a view to identify HF communication problem relevant to low latitudes

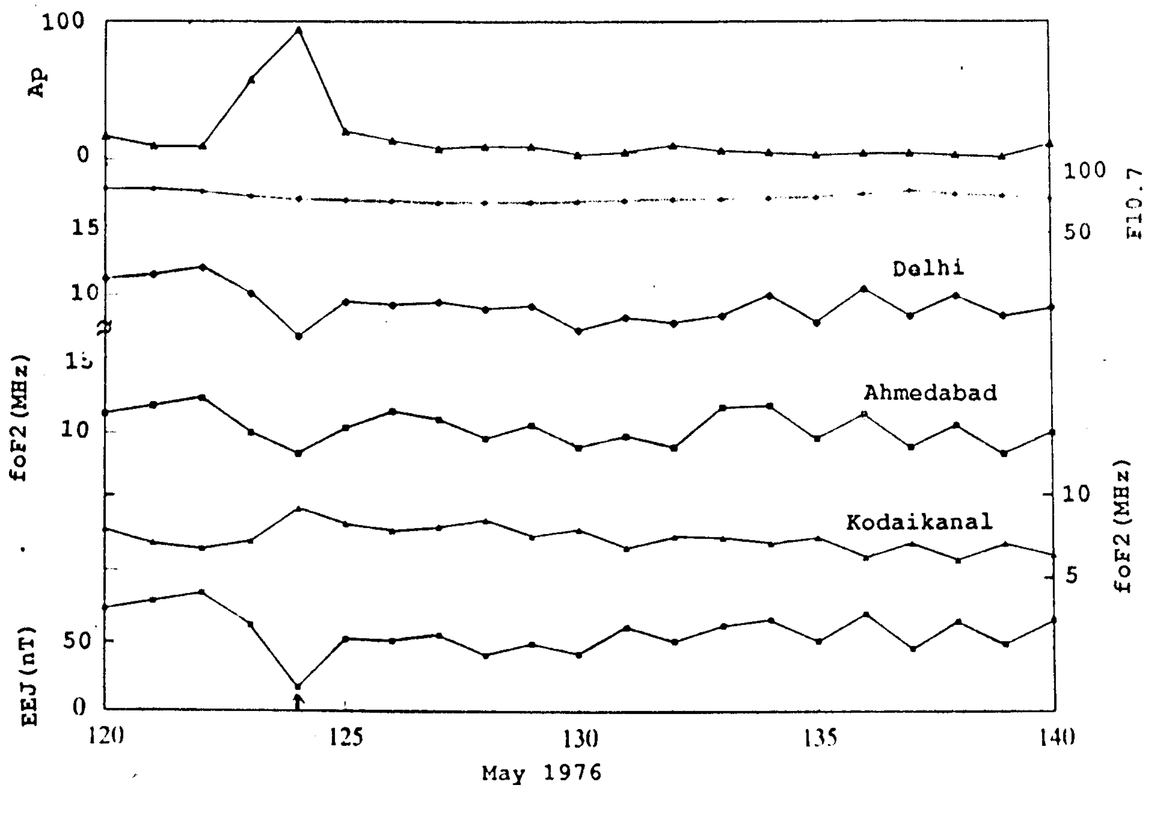

Figure 3. Shows the daily variation of noon time foF2 at Kodaikanal (Geo.Lat.10.2N), Ahmedabad (Geo.Lat.23N) and Delhi(Geo.Lat.28.6N) along with variations in Equatorial Electrojet strength (EEJ at 1000 LT), $F_{10.7}$ and A_p for the period 29 April – 19 May 1976. The arrow indicates 3 May 1976.

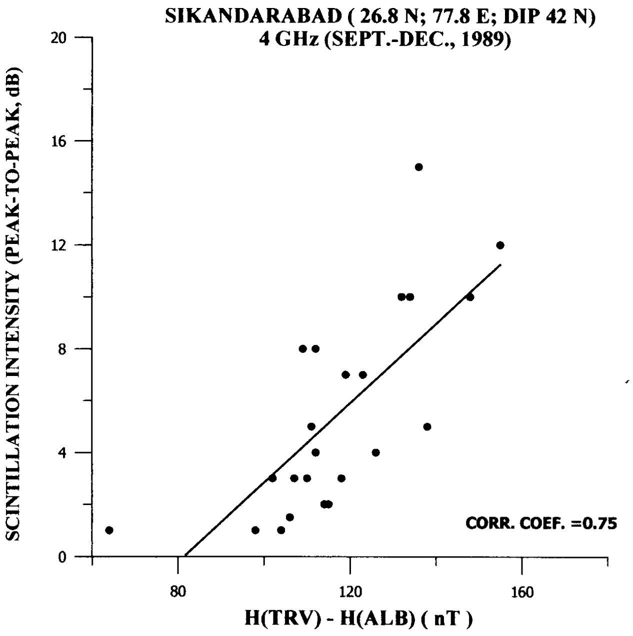

Figure 4. Relationship between daytime Equatorial Electrojet (EEJ) Strength and the Intensity of 4 GHz scintillations observed over Sikandarabad.

and has come out with appropriate remedial measures for different problems (Lakshmi et al. 1979). Consultancy services are being rendered routinely on HF communication to various users in India on request by NPL. A vexing problem of ionospheric F region in radio communication applications is the large day-to-day variability in F region electron densities apparently unrelated to usually monitored solar and geophysical indices (Aggarwal, Lakshmi & Reddy 1979). This problem is particularly severe at low latitudes where the extents of variability are very large especially around equatorial anomaly peak.

A new approach has been adopted to study this problem using Equatorial Electrojet (EEJ) strength as an index .We know that the distribution of ionization in low latitudes depends to a large extent on the EEJ strength. The f_oF_2 data sets obtained from Kodaikanal (Geo.Lat.10.2N), Ahmedabad (Geo.Lat. 23N) and Delhi (Geo.Lat. 28.6N)) in the Indian zone over a solar cycle were analyzed for their day-to-day variability using EEJ strength as an index. EEJ strength values were determined from H-field data of Trivandrum(dip 0.6N) an electrojet station and Alibag located at dip 35.5N. Fig.3 is an example showing the day-to-day variability trends in noon time foF_2 values for the period 29 April to 19 May 1976 at different stations in the Indian zone. The daily values of $F_{10.7}$, A_p and EEJ strength for 1000 hours are also plotted in the figure. It can be appreciated from the figure that there is an excellent correlation in day-to-day variability trends in f_oF_2 and that in EEJ strength. It can also be observed that no such correlation exists between f_oF_2 and $F_{10.7}$ or A_p on day-to-day basis. However, the sharp increase in f_oF_2 at Kodaikanal and decrease at Ahmedabad and Delhi values seen on 3 May is consequent to a magnetic disturbance (A_p about 100). The decrease in EEJ strength is due to the weakening of the east-west electric field during magnetic disturbances. The study suggests that for prediction of day-to-day variability trends in f_oF_2 and Total Electron Content (TEC) for various radio communication and navigation applications, electrojet srength can be a useful parameter. The electron density distribution in low latitudes can be predicted for a particular day a few hours in advance by knowing the EEJ strength. The EEJ strength indexing can also be used in certain critical trans-ionospheric propagation applications. These include the estimation of TEC and hence time delay in GPS applications; this can also be used for predicting the probability of low latitude scintillations especially during high solar activity years.

EQUATORIAL IONOSPHERIC SCINTILLATIONS

Radio scintillations due to presence of moving irregularities in the ionosphere is a major problem in navigation applications using Global Positioning Systems (GPS) and in satellite communication (SATCOM) especially in low latitudes. The problem is particularly acute around equatorial anomaly peak region . The down leg transponders of the Indian geo-stationary satellites used for telecommunication are in the 4GHz band because of the much more serious problems caused by tropical rain attenuation at higher frequencies. This makes the problem of ionospheric scintillation a matter of continuing concern. At Delhi scintillations as high as 24 dB peak-to-peak at 4 GHz have been observed during equinoctial months of high solar activity periods (Dabas et al. 1991).

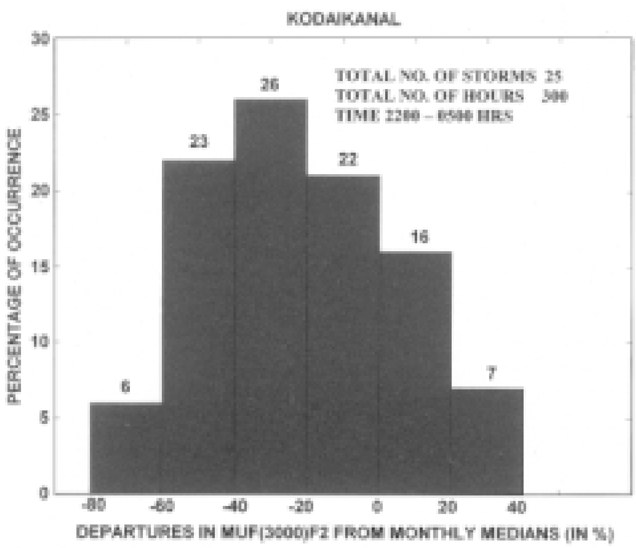

Figure 5. Histogram showing the distribution of percentage departures in MUF (3000) F_2 from monthly medians for Kodaikanal(Geo Lat.10.2N) during severe magnetic storms.

Satellite signals at 4 GHz from Indian satellites and also in VHF from FLEETSAT satellite are being monitored simultaneously at some key locations in India. Studies have been conducted on the occurrence probability of scintillations, their day-to-day variability and latitudinal extent. It has been observed that there exists a good correlation with day time EEJ strength and night time scintillation intensity at 4 GHz especially around equatorial anomaly peak region (Fig.4). Possibility of using EEJ as an index for predicting scintillations is being examined.

STORM- TIME IONOSPHERIC DEPARTURE MODELS

HF communications can be seriously disrupted during geomagnetic storms, especially so in high and mid latitudes. Ionospheric responses to magnetic storms are varied depending on the latitude, time of the day and severity of the storms. HF operators will be needing advance warnings of these events so that they can switch on to alternate frequencies during these periods based on the storm- time ionospheric departure models.

A model for prediction of ionospheric departures during magnetically disturbed periods for Indian region has been developed by NPL. In general the storm-time departures are modest and mostly positive during day time in low latitudes. However, both negative and positive responses are possible during night time (Lakshmi, Reddy & Shastri 1983). A study conducted using data pertaining exclusively to severe magnetic storms has shown that night time decreases in f_oF_2 values can be very sharp and sudden at equatorial latitudes(Lakshmi et al. 1997). Large negative departures in MUF(3000)F_2 values(Maximum Usable Frequencies for a path length of 3000km) from monthly medians by as much as 60% have been observed during night time when the main phase of the storm is in progress which can result in serious disruptions to radio communications in HF bands.Providing storm–time ionospheric predictions to HF users is an integral part of NPL's over all prediction services.

Based on an analysis of night time departures in MUF (3000)F_2 values during a large number of severe storms (maximum K-index at Alibag greater than or equal to 7) from their respective monthly medians at Kodaikanal (10.2N. Geo.Long. 77.5E) a histogram (Fig.5) is drawn to show the distribution of percentage departures in MUF (3000)F_2 values. The histogram includes data for 300 disturbed hours. It can be noted from the histogram that 77% of the departures in MUF (3000)F_2 values are of negative kind with 26% of the values being in the range of 20 - 40% below medians, and 23% in the 40 - 60% range below medians. It is obvious from the histogram that during nighttime negative departures far exceed the positive departures during these magnetic storms. A similar histogram is also obtained using percentage departure data of MUF(3000)F_2 for Manila (Geo.Lat.14.7N, Geo.Long.121E) in the eastern zone. It was noted that more than 75% of the departures in MUF(3000)F_2 values are of negative kind with 30% of these values being below the medians by 20 - 40%.

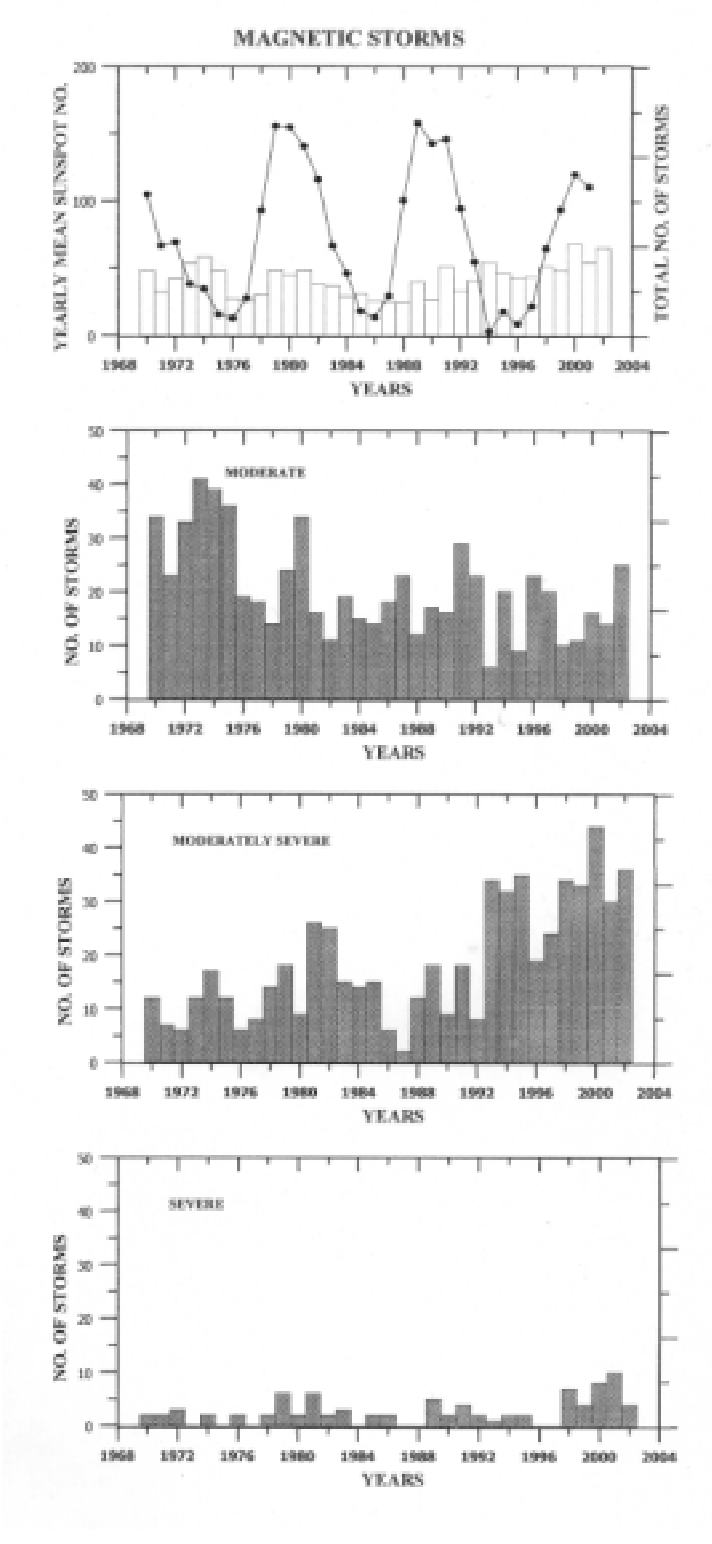

Figure 6. Top panel shows yearly occurrence of Magnetic Storms (Alibag and Hyderabad) for the period 1972 – 2002 along with yearly mean Sunspot Numbers. Yearly occurrence of moderate, moderately severe and severe storms are shown separately in the lower panels for the same period.

This study clearly indicates that during severe magnetic storms the low and equatorial latitude night time ionospheric responses can be very large and negative. This observation is at variance with the understanding of low latitude ionospheric responses to magnetic storms in general.

MAGNETIC STORM PREDICTION

The prediction of magnetic disturbances on short term basis has gained great importance in recent decades because of its application potential in a wide variety of areas of human interest, such as HF radio systems, satellite based radio systems, tracking of low orbiting satellites, manned space flights, biological systems etc. In fact this is a major focus of several space weather studies around the world.

Thanks to the excellent opportunities offered by satellite based instrumentation, we have now access to a variety of observational information on solar and geophysical parameters. This new information includes data on Interplanetary Magnetic Field, solar wind, solar particle emissions, X-rays, Coronal holes, Coronal Mass Ejections (CMEs) etc. This is in addition to the information on solar events obtained from ground based optical and radio frequency experiments.

Geomagnetic storms have fascinated the civilized society for a very long time. Perhaps the biggest storm ever recorded occurred in September 1859 with a Dst above – 1700 nT and Colaba Observatory, India recorded a Dst of –1600 nT (Tsurutani et al. 2003)

Geomagnetic storms are known to occur consequent to intense clouds of solar energetic particle emissions associated with solar flares, Coronal Mass Ejections or Coronal hole efflux. One of the most important results of earlier studies on solar-terrestrial relations was regarding magnetic storm occurrences following solar flares accompanied by meter-wave length Type II and Type IV radio bursts. Type II and type IV bursts are considered as useful precursors to magnetic storm occurrences as they represent the generation of shocks and ejecta respectively. The arrival of a shock at terrestrial levels can be recognized as a sudden increase in the magnetic field (Sudden Commencement). However, recent studies made during the last two decade or so using information on CMEs have totally changed the above scenario. It is now very well established that most of the geomagnetic storms especially the Sudden Commencement (S C) type owe their origin to CMEs (Gosling et al 1990; Gosling 1993; Kahler,1992). It is also observed that magnetic storms are associated with disappearing filaments on the solar disk (Joselyn 1986) and disappearing filaments are also observed to be closely related to CMEs. Existence of a high degree of association between CMEs and long duration soft X-ray events [LDEs] has also been observed (Sheeley et al, 1993; Webb & Hundhausen 1987; Webb 1992). Hence, disappearing filaments and LDEs can be useful diagnostics in prediction of magnetic storms. There are also a number of studies to show one-to-one correspondence between CMEs and interplanetary shock waves (Sheeley et.al. 1985; Schwenn 1993). A number of studies conducted on geomagnetic activity in relation to Interplanetary Magnetic Field (IMF) direction (B_z) have shown that there is a good correlation between southward component ($-B_z$) of the IMF and geomagnetic activity (Tsurutani et al. 1988; Tsurutani et al. 1992). Intense magnetic storms have been found to be associated with long duration, large magnitude south component intervals ($-B_z$) events. Hence, information on direction, intensity and duration of $–B_z$ becomes critical to predicting geomagnetic storms.

An important aspect of magnetic storm prediction is the severity of storm once the probability of occurrence of a storm is assessed after solar event like CME or LDE is observed. The magnetic storms reported by Alibag observatory (18.7N, 73 E) and Hyderabad (17.4 N, 78.5 E) during 1970 - 2002 have been examined to study some of these aspects.

In Fig.6 the top panel shows year-wise occurrence of magnetic storms for the period 1970 – 2002 along with yearly mean sunspot numbers. The year-wise distribution of moderate (Maximum K = 4 or 5), moderately severe (Maximum K= 6 or 7) and severe (Maximum K = 8 or 9) storms are shown separately in the lower panels. There are some interesting points that can be noted from this composite diagram regarding yearly distribution of magnetic storms during the period 1970-2002. Firstly , occurrence rate of magnetic storms is comparatively higher during the years 1990-2002. While the occurrence rate of moderate storms shows a decreasing tendency, the moderately severe storm occurrence increases sharply during the same period. Severe storm occurrences are also high particularly during the years 1998-2002. The results displayed in the diagram seem to imply that there is a longterm trend of increase in magnetic activity since 1990 if one considers all categories of magnetic storms.

CONCLUSION

The space science and technology are advancing rapidly influencing every aspect of our daily activities. Also, the concerns of global change include longterm changes in solar output and the sun-weather connection. The main objectives of this paper are to bring the latest in the area of Solar–Terrestrial predictions to the notice of the Geophysical research community and report some of the recent developments in the field at the National Physical Laboratory, New Delhi. The long term solar and ionospheric predictions at NPL are among the best in the world and are available on request. Based on inputs from international organizations, daily predictions are also issued for critical users. This however falls short of a state of the art space weather prediction which should include proton events, energetic particle flux predictions and flare probabilities. The future efforts should be to identify appropriate indices most suitable for different applications. For example, for long term HF communication predictions sunspot number is fine, while EUV indexing should be explored for short term ionospheric predictions as well as for planning of LEO satellite parameters. The CME and flare indices that can be derived from ground -based and satellite- based observations will be most suited for space weather effects on orbiting as well as geo-stationary satellites.

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