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Australian Regional Ionospheric Disturbance Index based on the Principal Component Analysis and GPS Data

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Outline:

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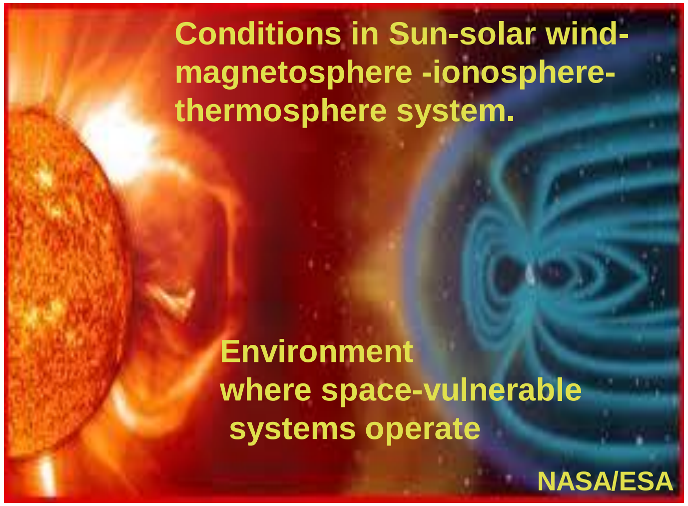
- Regional monitoring of the ionosphere
- Eignmode Decomposition
- Space Weather Indices/Forecast
- Application of the disturbance Index approach: Test Cases
- Conclusion/Future work

Introduction

Space Weather Envirenment

Changes in the interconnected system from the Sun to the Earth.



-Operational radio systems sensitive to current space weather conditions need reliable information as fast and as good as possible.

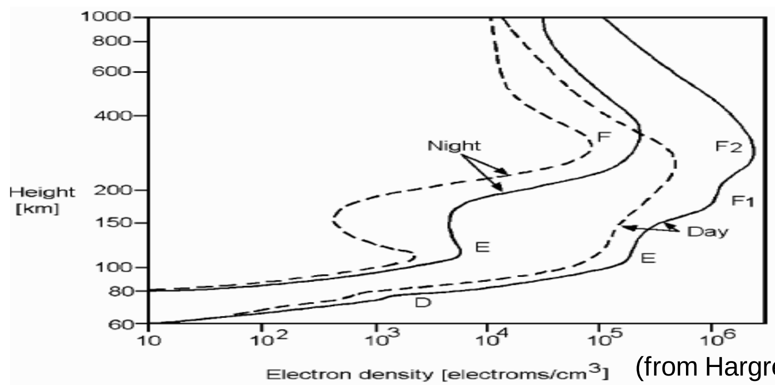
-Space weather impacts radio waves travelling through the ionized part of the Earth's atmosphere***(ionosphere/plasmasphere***).

Plasma Control Envirenment

Vertical structure: D, E, F1 and F2 layers

-**Spatial variation:**
~3 geographical regions / different behaviors.
(Equatorial/ low latitude, Mid-latitude ,Polar/high latitude)

-Temporal variations: connected to the solar activity
-Short-scale disturbances:
(Ionospheric storms, Traveling ionospheric disturbances (TID)s)



(from Hargreaves, 1992)

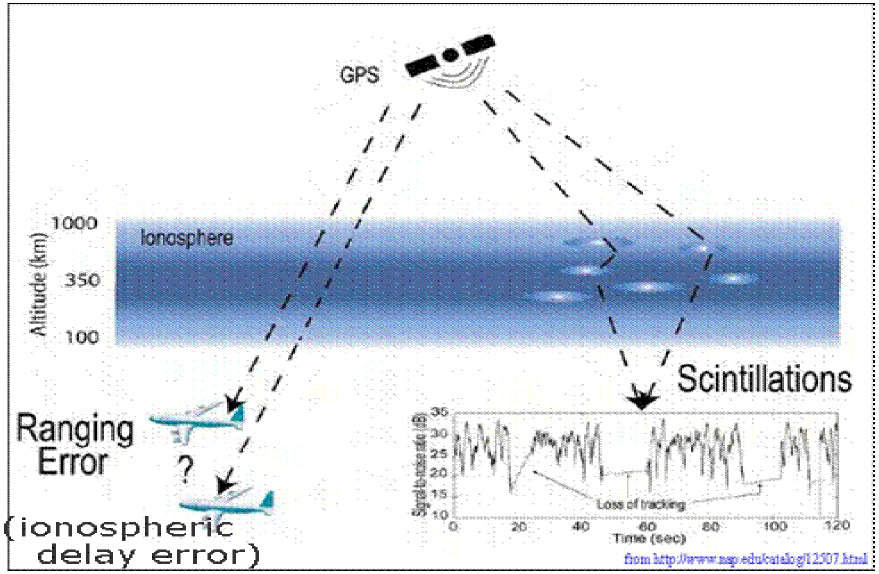
Structure and dynamics of the ionosphere are strongly controled by the solar radiation and the solar wind and coupled with the magnetosphere, thermosphere and lower atmosphere.

Ionspheric impact

Effect on radio wave propagation (on various areas):

-Global Navigation Satellite Systems (GNSS) are severely affected

-Ionospheric ranging error /Ionospheric delay
-Ionospheric gradients



- Ionospheric scintillation

-High variability of GNSS signal strength (radio scintillations)
-Can be severe enough to cause loss of lock (no signal availability) on one or more GPS satellites, reducing positioning accuracy.

Ionospheric perturbations (Ionospheric storms **):**
-Degrade precise positioning services
-Affect Safety of Life (SoL) applications of GNSS.

Near real time detection and forecasting of ionospheric storms: Probability of a possible impact
$\Rightarrow$ **Users WARNING**
$\Rightarrow$ **Risk assessment of violating:** Accuracy bounds/ Protection levels

Detection / monitoring of ionospheric threats:

- **Geomagnetic and ionospheric storms are strongly couplled**
- **Preliminary indicator: Geomagnetic indices**

Geomagnetically based probability of ionospheric perturbations:

Degree of perturbation	Kp	Number of events from 1995-2012
Minor	5	1076
Major	6	344
Severe	8	194
extreme	9	4

Geomagnetic indices (Kp, Ap, and Dst)
-Important in modelling and characterizing the perturbation degree of the geospace.
-Characterize the planetary perturbation quite well
NOT a correct description of the perturbation degree of the local or regional ionosphere.
-Temporal resolution: in the order of 1–3 h
NOT sufficient to fulfil customer needs.

The ionosphere reacts quite different on space weather factors depending on time and geographic/geomagnetic location.

-GNSS users need more accurate information.

-Geomagnetic indices do not really match to customer needs to receive correct ionospheric weather information in near real time.

Proposed Disturbance Index

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Actual and reliable index which describes the regional ionospheric state with a potential to be used in operational applications !!!

Requirements:

-Objective measure of the ionospheric perturbation
The complex information is condensed in a simple number
(can easily be fed into user algorithms and models.)

-Relevance to practical needs
-Match to customer needs to receive correct ionospheric weather information in near real time

-Availability of reliable database
-Continuous computation
-Provision in near real time streaming mode
-Well suited for forecasting

Total **E**lectron **C**ontent **(TEC)** (electron concentration over the local vertical).

Dual frequency measurements ⇒ Total Electron Content (TEC):

$$TEC = \int_R^S n_e ds$$

~ ionospheric range error(1st order)

-Outstanding parameter for quantifying the range error and also the strength of ionospheric perturbations.
-The availability of such data is permanently increasing which improves the conditions for estimating the disturbance index with a good performance.

Regional monitoring : Spherical Cap Harmonic Analysis (SCHA)

- GNSS applications are in particular sensitive to spatial gradients and temporal variability of TEC.

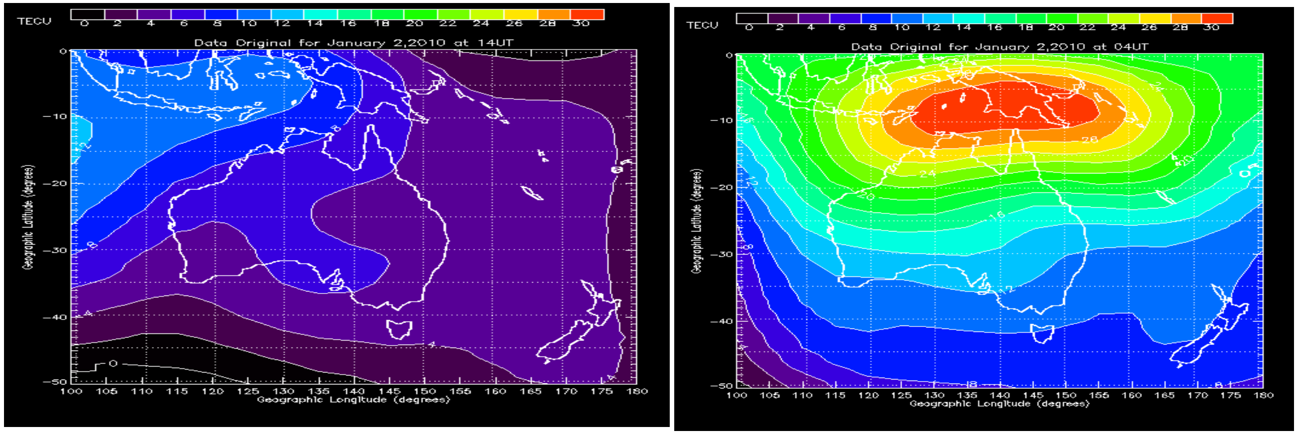
-To fulfil user needs we focus on ionospheric perturbations which are characterized by a high spatial and temporal variability.

-SCH model for mapping the Australian Regional TEC:

$$VTEC(\theta_c,\lambda_c) = \sum_{k=0}^{K\max}\sum_{m=0}^{K} P_{nk(m)}^{m}(\cos(\theta_c)\left[g_k^m \cos(m\lambda_c) \quad + h_k^m \sin(m\lambda_c)\right]$$

(Haines,1985) ***k*** $\Rightarrow$ ***n k*(*m*)** Non integer degree ($\theta_0 \neq \pi$)

SCHA accommodates spatially confined observations without having to redistribute the data coordinates over the earth.



-Reconstruction of regional ionosphere needed for getting reliable information

Regional TEC map on 02/01/2010 at 04:00UT(right) and 15:00UT(left)

Eignmode Decomposition: PCA

z(t,x) Matrix of N Regional TEC maps at P locations (N: Number of hours (January –December, 2010).

-Spatial structures: $E_j(\theta,\varphi)$ Eigenvectors (Basis Function) (generated directly by themselves) (ranged in descending order according to the proportion of variance explained)

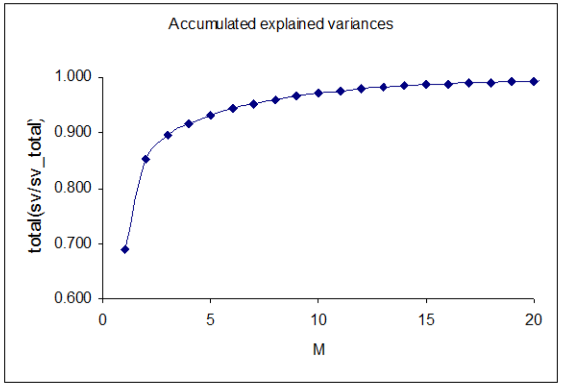
-Their time evolution :

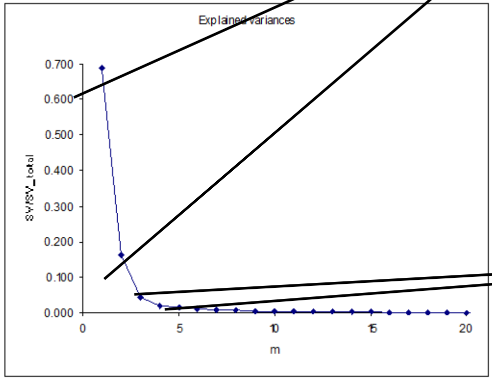
$$A_j(t) = z'^T(t,\theta,\varphi)E_j(\theta,\varphi)$$

(uncorrelated and carrying information about the variation of TEC along E_j)

Dynamic approach: Ignoring smooth and slowly developing variations (first 2 components)
-Seasonal variation and the solar dependence of the background TEC over Australia. "Regional Climatology"

-The meteorology of the regional TEC perturbation is investigated.





-With decreasing variance PCs explain increasingly complex features

-As PCs are not correlated with each other they offer an added advantage as predictors .

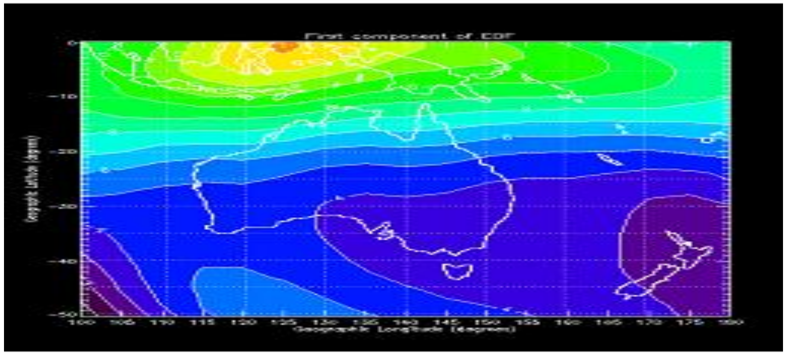
"Meteorology"

Explained variance and the accumulated explained variance for the TEC .

Seasonal variation and the solar dependence of the background

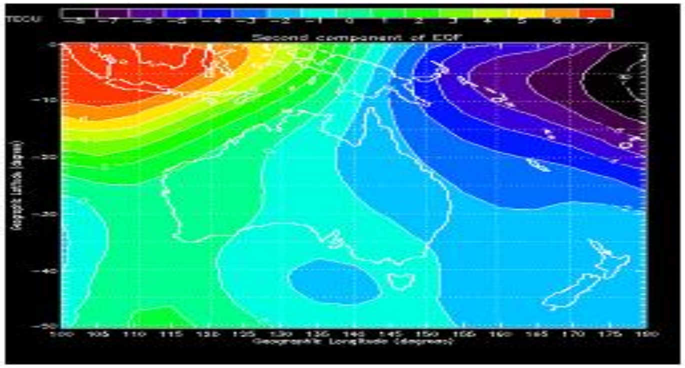
Significance: 69.7%

A1E1 mainly controls the intensity of the Ionospheric electron concentration.



Significance: 16.3%

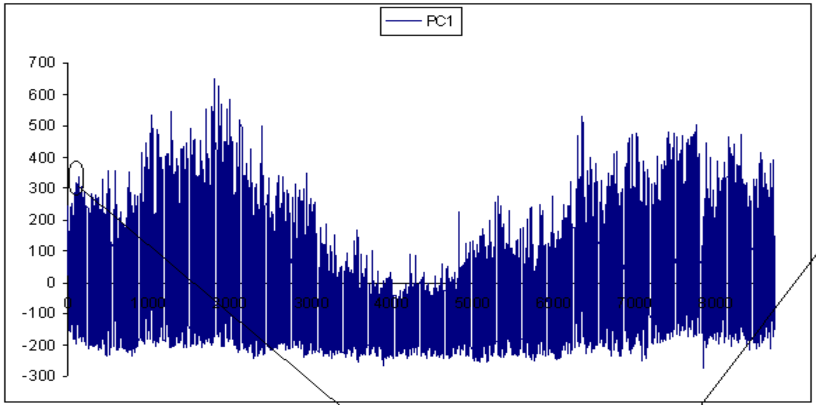
A2E2 : the correction of the main trend.



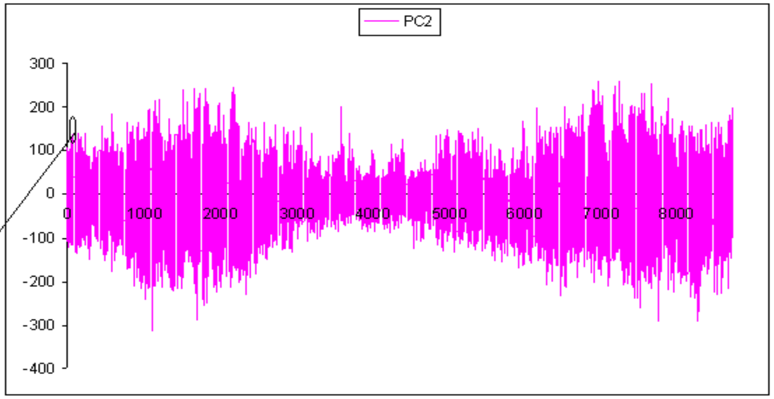
First two EOFs of the TEC for the year 2010, function of longitude and latitude

A1: Semiannual : 2 maxima

(March/April and September/October).



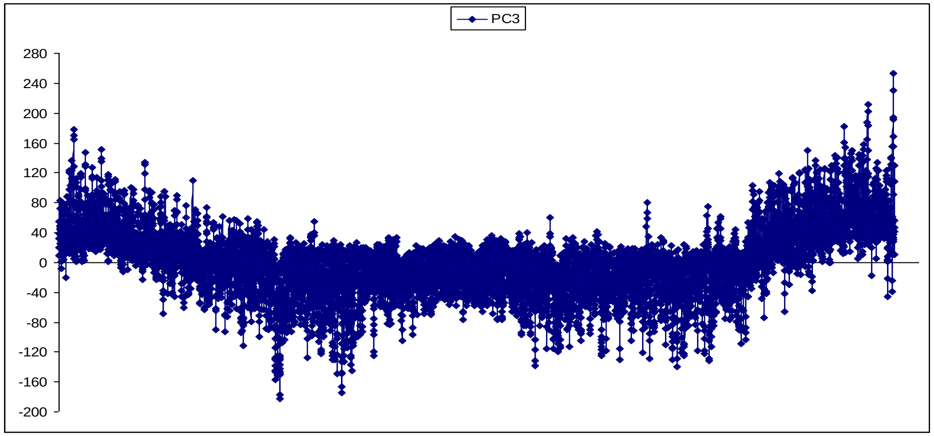
A2: Annual variation



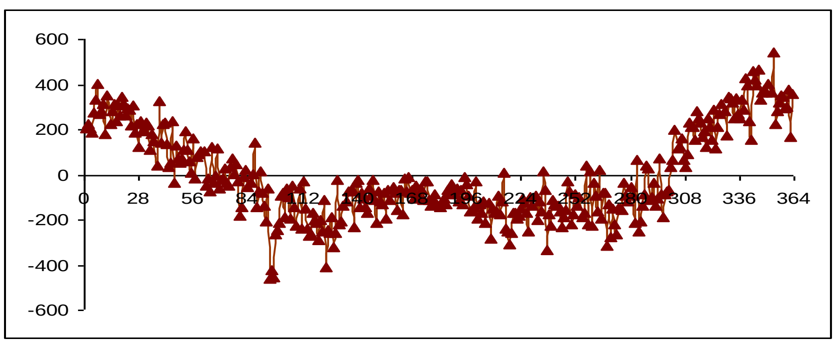
Time series of the first 2 EOFs coefficients shown above (*A1*, *A2*) (blue, pink) for the year 2010.

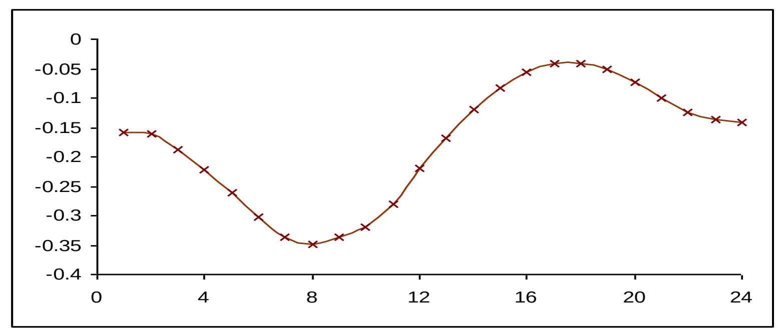
Higher order components: PC3

-Present mainly short-term variation and noise
-Less correlated with the primary variation in TEC.



Time series of the third component for the year 2010.





Bases function representing the variation with universal time and associated coefficient representing the seasonal variation.

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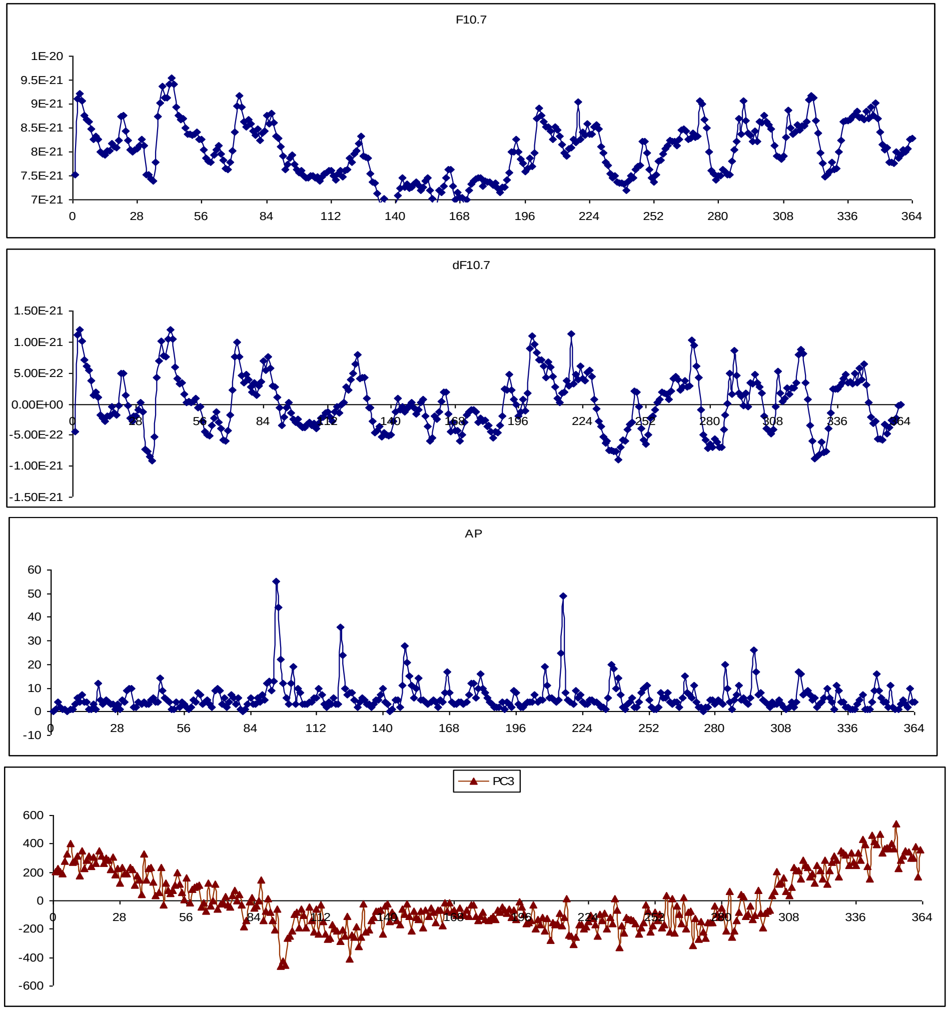
Space Weather Indices and TEC perturbation



Daily TEC perturbation, solar activity index(F10.7), deviation of F10.7 and geomagnetic activity index Ap.

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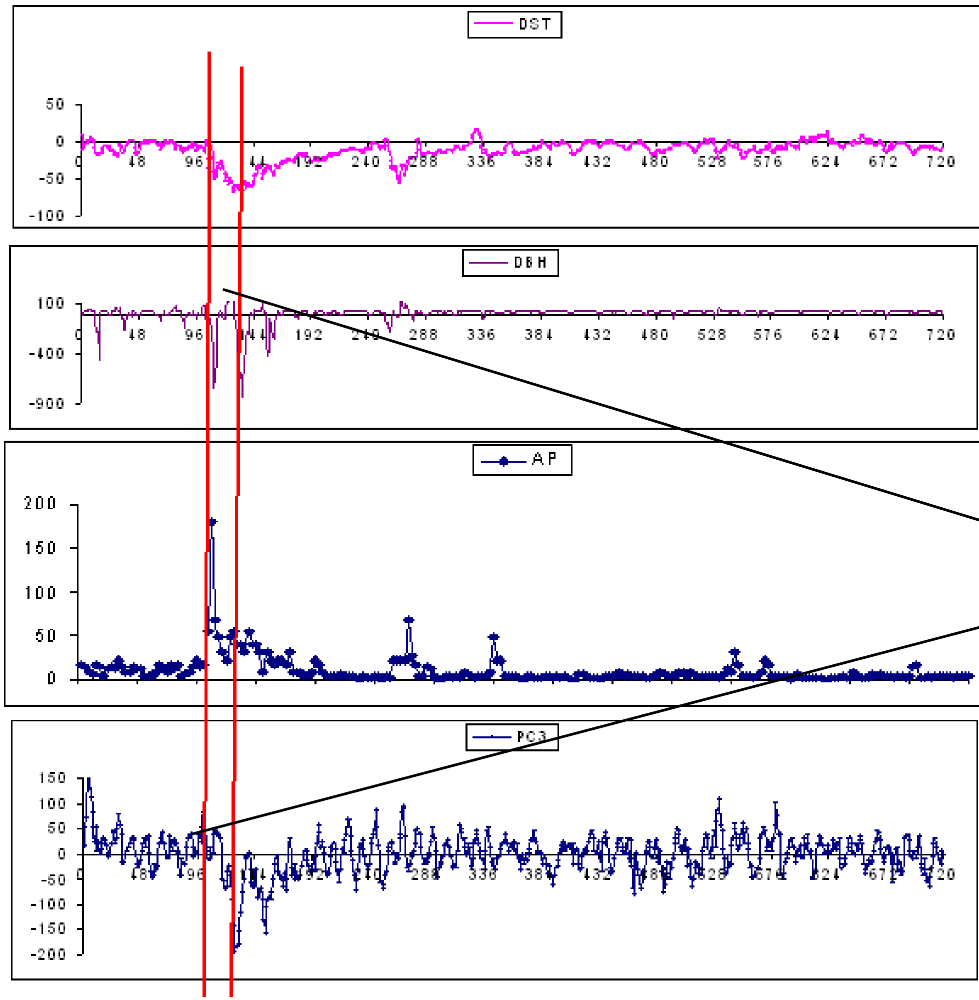
Space Weather Indices and TEC perturbation: April 2010



Most influential factors

Factors	F10.7	dF10.7	AP	Dst
Correlation	0.23	0.38	0.51	0.43

-Delayed perturbation acros the region

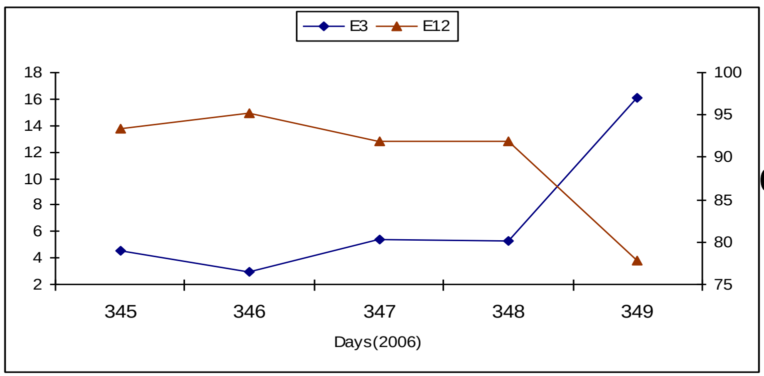
-Potential for predictionbased on earlier space weather observations

Comparison of daily Dst index (a), change in the geomagnetic field’s horizontal component at Canberra (b), Ap index (c) and TEC perturbation (d) over the Australian region (April 2010).

Application of the approach (test cases): December 2006 Geomagnetic Storm

Probable CME observed by SOHO satellite

Probable CME (UTC)	Class
13 Dec 02:40	X3.4
13 Dec 14:23	C2.2
13 Dec 18:25	C1.7
14 Dec 12:10	C1.0
14 Dec 16:49	C1.2
14 Dec 22:15	X1.5



Storm dynamics:

-Three interrelated causal mechanisms: mechanical, electrical and chemical.

-Competition among electric fields as well as thermospheric dynamics and composition changes.

Complex (Incomplete knowledge)

Development of the storm:

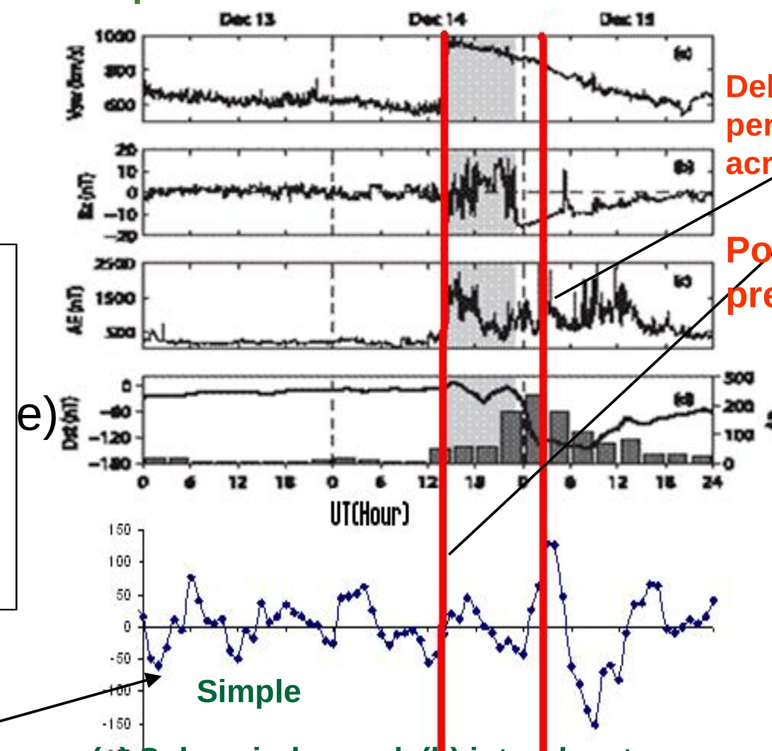
-Solar flares and Sunspots associated with large CMEs

-Change in Dst index (SSCs)

-Severity of the disturbed geomagnetic conditions (Ap Index)

- Rapid direction changes in the IMF Bz component and the Solar Wind .

Ap: 5 63 104



Delayed perturbation across the region

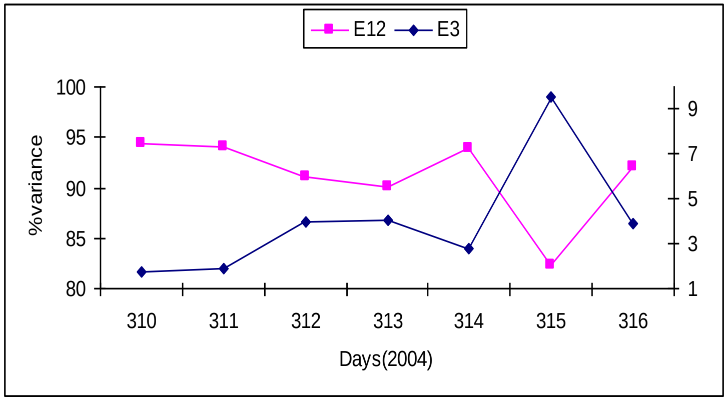
Potential for prediction

Simple

(a) Solar wind speed, (b) interplanetary magnetic field Bz, (c) AE index, (d) Ap and Dst index and (e) ionospheric perturbation on 13–15 December 2006. The patches indicate the initial phase of this storm.

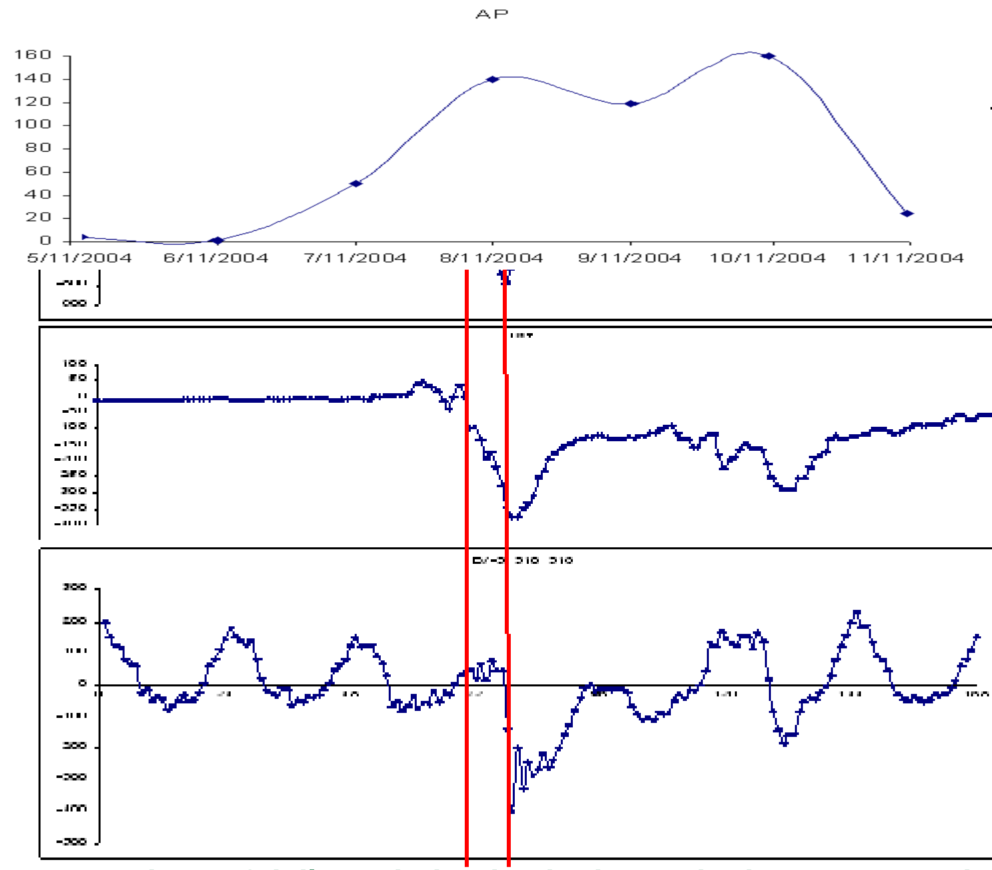
Application of the approach (test cases): November 2004 Geomagnetic Storm

5-11 November 2004



-The largest components(PC1 and PC2)
-Capture the slow-varying trends
- Primarily deterministic

-Lower component (PC3)
- short-term variation



Comparison of daily Ap index (top), change in the geomagnetic field's horizontal component at Canberra (middle) and TEC perturbation (bottom) over the Australian region.

Conclusion:

- A new Ionosphere Disturbance Index is established through the statistical Eigen mode analysis based on GPS measurements with great practical value in operational applications.

- A regional dynamic approach with high temporal and spatial resolution sufficient to meet the need of the ionosphere variability study and the demand of practical application like the GNSS-based navigation and positioning.

- Potential for prediction and related performance changes in GNSS applications using early space weather information.

- The next step of this research is to translate the ionospheric parameters describing the perturbation degree into users terms.