# New space weather service for monitoring and forecasting Regional Ionospheric Perturbations over Australia based on GNSS techniques.

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**Abstract:**

Ionospheric perturbations can degrade precise positioning services and affect Safety of Life (SoL) applications of Global Navigation Satellite Systems (GNSS). Near real time detection and forecasting of ionospheric perturbations might warn users of a potential degradation of the performance of these systems. In this paper, a new Australian Regional Ionospheric Disturbance Index (AusRDI) is introduced based on a regional dynamic approach ignoring smooth large scale and slowly developing deviations. The Spherical Cap Harmonic Analysis (SCHA) method was firstly used to estimate TEC at evenly distributed grid points from GPS data collected from the Australian Regional GPS Network (ARGN). The SCHA model is based on longitudinal expansion in Fourier series and fractional Legendre co-latitudinal functions over a spherical cap-like region including the Australian continent. This harmonic expansion requires fewer coefficients to represent the fine structure of regional ionospheric features and may be adapted to take advantage of regions of densely distributed observations in order to observe and model ionospheric dynamics over Australia on a range of spatial scales. Principal Component Analysis (PCA) was then used to decompose the TEC dataset into a series of orthogonal Eigenfunctions (EOF base functions) and associated coefficients. PCA is non parametric and as such does not utilize deviation from a previously described average to determine perturbations. The new disturbance index provides an objective measure of ionospheric perturbation processes reflected in small spatial and rapid temporal variations. Furthermore the index is predictable using early space weather information. Such index can provide reliable information and has great practical value for operational radio systems sensitive to current space weather conditions.

## Ionospheric perturbation detection and monitoring:

**Geomagnetically based detection of ionospheric perturbations:**

- -Ionospheric perturbations are strongly couplled with severe disturbances in the magnetic field
- -Preliminary indicator of the perturbation: **Geomagnetic indices** (Kp, Ap, and Dst… )
- -Modelling and characterizing the planetary perturbation degree.
- - 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. )

| Degree of perturbation | Kp |
|---|---|
| Minor | 5 |
| Major | 6 |
| Severe | 8 |
| extreme | 9 |

-Ionospheric response to space weather factors depends on the time and location.
-Geomagnetic indices do not really match to customer needs (ionospheric information in near real time).

**Proposed TEC based Ionospheric Disturbance Index:**

Actual and reliable index which describes the regional ionospheric state to be used in operational applications.

**-Objective measure of the the regional ionospheric state**
**-Relevance to practical needs**
**-Suited for forecasting**

**Parameter for quantifying the range error and also the strength of ionospheric perturbations: T**otal **E**lectron **C**ontent (**TEC**) (electron concentration over the local vertical).

$$TEC = \int_R^S n_e ds$$ **~ ionospheric range error(1st order)**

Dual frequency measurements ⇒ TEC

## Regional monitoring : Spherical Cap Harmonic Analysis (SCHA)

-To fulfil user needs we focus on ionospheric perturbations which are characterized by a high spatial and temporal variability.
*GNSS applications are in particular sensitive to spatial gradients*

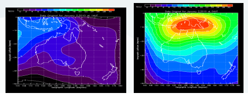
**-SCH model for mapping the Australian Regional TEC:**

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

**(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).**

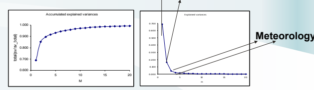
## Eignmode Decomposition (Lin, 2011) : PCA

**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 (Londono et *al.,* 2005)).
**-Their time evolution :**

$$A_j(t) = z^{\prime T}(t,\theta,\varphi)E_j(\theta,\varphi)$$

(uncorrelated and carrying information about the variation 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 ( Mao et *al.,* 2005). "Regional Climatology"




**Explained variance and the accumulated explained variance**

-With decreasing variance PCs explain increasingly complex features

-The meteorology of the regional TEC perturbation is investigated.

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

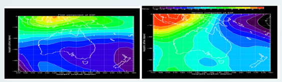
## Seasonal variation and the solar dependence:

### Seasonal variation:

**Low frequency components (first components)**

**Significance: 69.7%**
A1E1 mainly controls the intensity of the Ionospheric electron concentration.

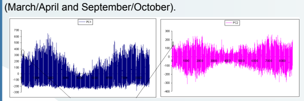
**Significance: 16.3%**
A2E2 : the correction of the main trend.



**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**



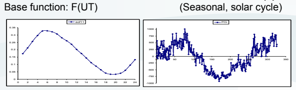

**Time series of the first 2 EOFs coefficients shown above (*A1*, *A2*) (blue, pink) for the year 2010.**

### Solar dependence:

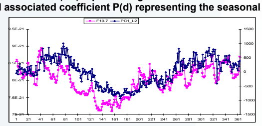
**Second layer decomposition:**
Eigenvalue decomposition of $A_1$(UT,d)

**EOF**
Base function: F(UT)

**EOF coefficient P(d)**
(Seasonal, solar cycle)



**Base function F(UT) representing the variation with universal time and associated coefficient P(d) representing the seasonal variation.**



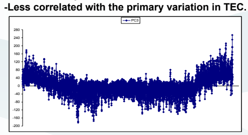

**Coefficient of second layer decomposition (P(d)) (blue) and F10.7 (pink), ( 10.7-cm solar radio flux** in units of W m-2Hz-1**).**

-The patterns of P(d) and F10.7 cm flux are quiet consistent (r= 0.74 )
-Contribution of the first component is 70% ⇒ solar activity is the dominant factor that controls TEC variability.

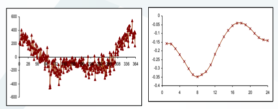
## Ionospheric perturbation:

**Higher order components:** Perturbation

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



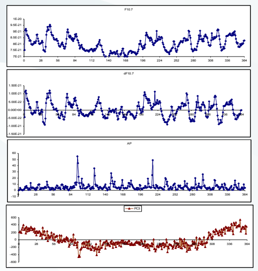

**Time series of the third component for the year 2010.**



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

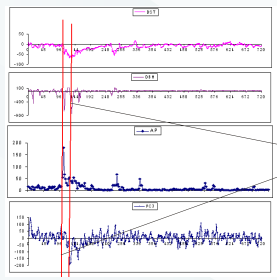
## Space Weather Indices and TEC perturbation

**Year 2010**




**Daily TEC perturbation, solar activity index(F10.7), deviation of F10.7 and geomagnetic activity index Ap (2010).**

**April 2010**




**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).**

**Most influential factors**

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

**-Delayed perturbation across the region**

**-Prediction based on earlier space weather observations**

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

Probable CME observed by SOHO satellite

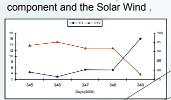
| Probable CME (UTC) | Class |
|---|---|
| 13 Dec 02:40 | X3.4 |
| 13 Dec 14:23 | C2.2 |
| 13 Dec 18:25 | C1.7 |
| 14 Dec 12:10 | C1.0 |
| 14 Dec 16:49 | C1.2 |
| 14 Dec 22:15 | X1.5 |

**Development of the storm:**

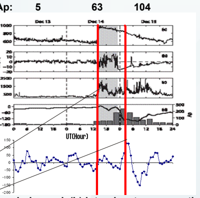
-Solar flares and Sunspots associated with large CMEs
-Change in Dst index (SSCs)
-Severity of the disturbed geomagnetic conditions (Ap Index)
- Rapid direction changes in the IMF Bz component and the Solar Wind .

**Storm dynamics:**

-Three interrelated causal mechanisms: mechanical, electrical and chemical.
-Competition among electric fields as well as thermospheric dynamics and composition changes.



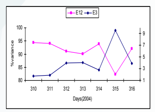

**-Delayed perturbation across the region**



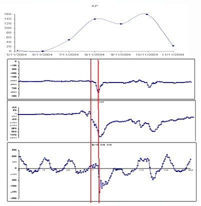

**(a) Solar wind speed, (b) interplanetary magnetic field Bz, (c) AE index, (d) Ap and Dst index and (e) ionospheric perturbation on 13–15 December 2006. The patches indicate the initial phase of this storm.**

## Application: 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/ Future work:

**-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 practical application such as GNSS-based navigation and positioning.**
**-Potential for prediction and related performance changes in GNSS applications using early space weather information.**

## References:

-**Haines**, G.V., 1985,"Spherical Cap Harmonic analysis", J.geophys.Res.,90,2583—2591.
-**LIN** Jyh_Woei, 2011," Latitude_Time TEC anomalies as precursors to Japan's Earthquake associated with principal Component Analysis", International Journal of Geophysics, doi: 10.1155/2011/763527.
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- **MAO** Tian, WAN Wei-Xing, LIU Li_Bo,2005," An EOF based Empirical Model of TEC over Wuhan", Chinese Journal of Geophysics, 48, No 4, 827-834.