Investigation of earthquake signatures on the Ionosphere over Europe

Haris Haralambous[1], Christina Oikonomou[1], Buldan Muslim[2]

[1] *Frederick Research Center, Cyprus*

[2] *Space Science Center, Indonesian National Institute of Aeronautics and Space*

14th International Ionospheric Effects Symposium

"Bridging the gap between applications and research involving ionospheric and space weather disciplines"

IES2015
May 12-14, 2015

Introduction

- The last 2 decades, the link between seismic activity and ionospheric perturbations related to earthquake precursory phenomena has acquired significant attention

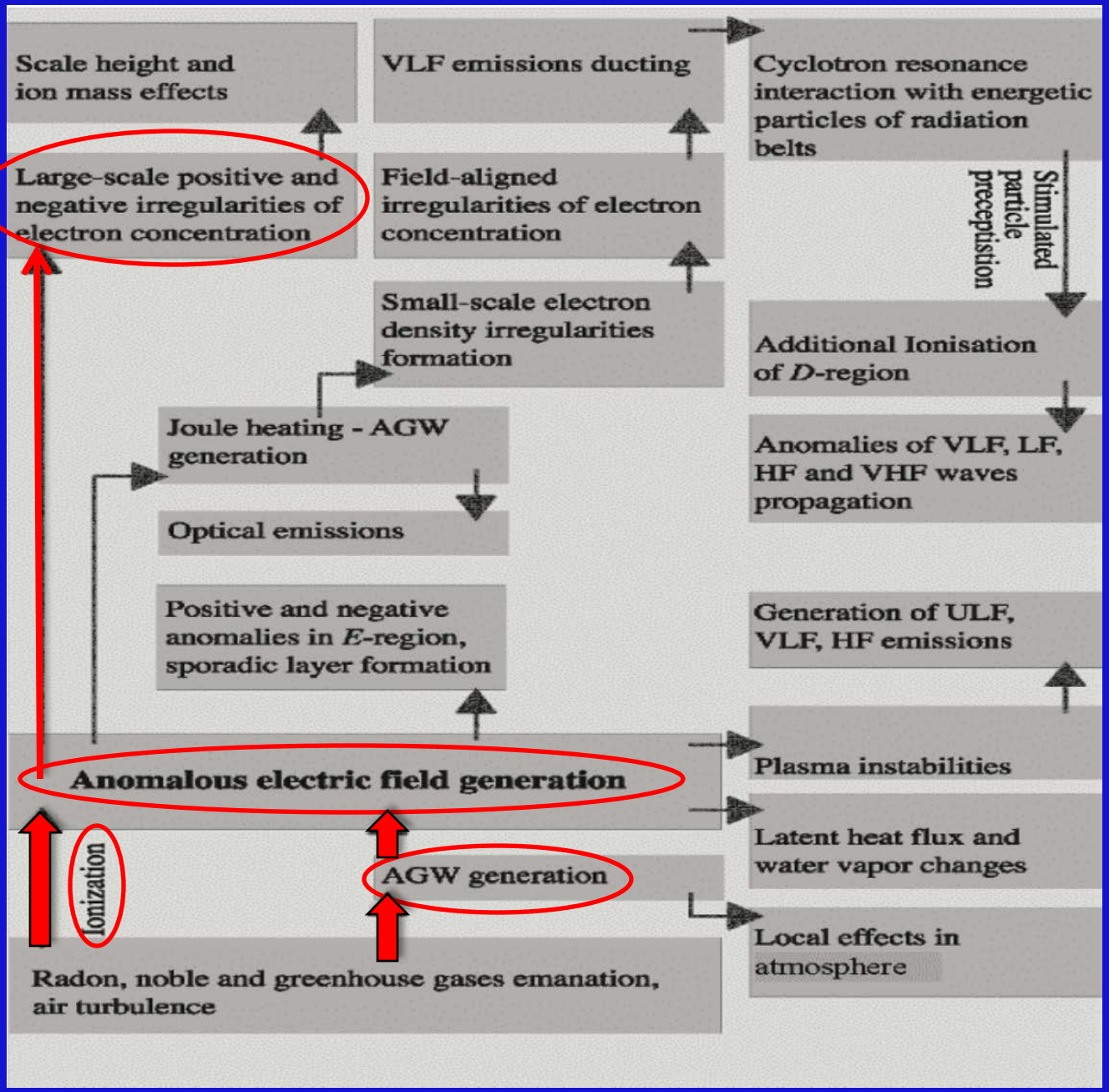
- Some possible earthquakes precursors are: ground deformations, radon/helium emissions, crustal stress, atmospheric thermal anomalies

- The physical mechanism of lithosphere-atmoshere-ionosphere coupling is based on the fact that **gas emissions** prior to an earthquake cause:
- a). **Ionization** of the neutral atmosphere above the epicenter which generates **Anomalous electric field** that penetrates the ionosphere leading to large-scale positive and negative **anomalies of electron concentration** in the vicinity of the epicenter
- b). **Atmospheric Gravity Waves** (AGW) which generate anomalous electric field as well.

- The aim of this study is to investigate the possible correlation of ionospheric perturbations prior to earthquake with seismic activity by applying two different analysis techniques:

- **a). Cross-Correlation Analysis**
- **b). Spectral Analysis**

- Using GNSS and Ionosonde observations
- over the European area
- for earthquake events with magnitude (Mw) greaten than 5.9
- during the period 1998-2013



Block Diagram of Seismo-Ionospheric Coupling Model

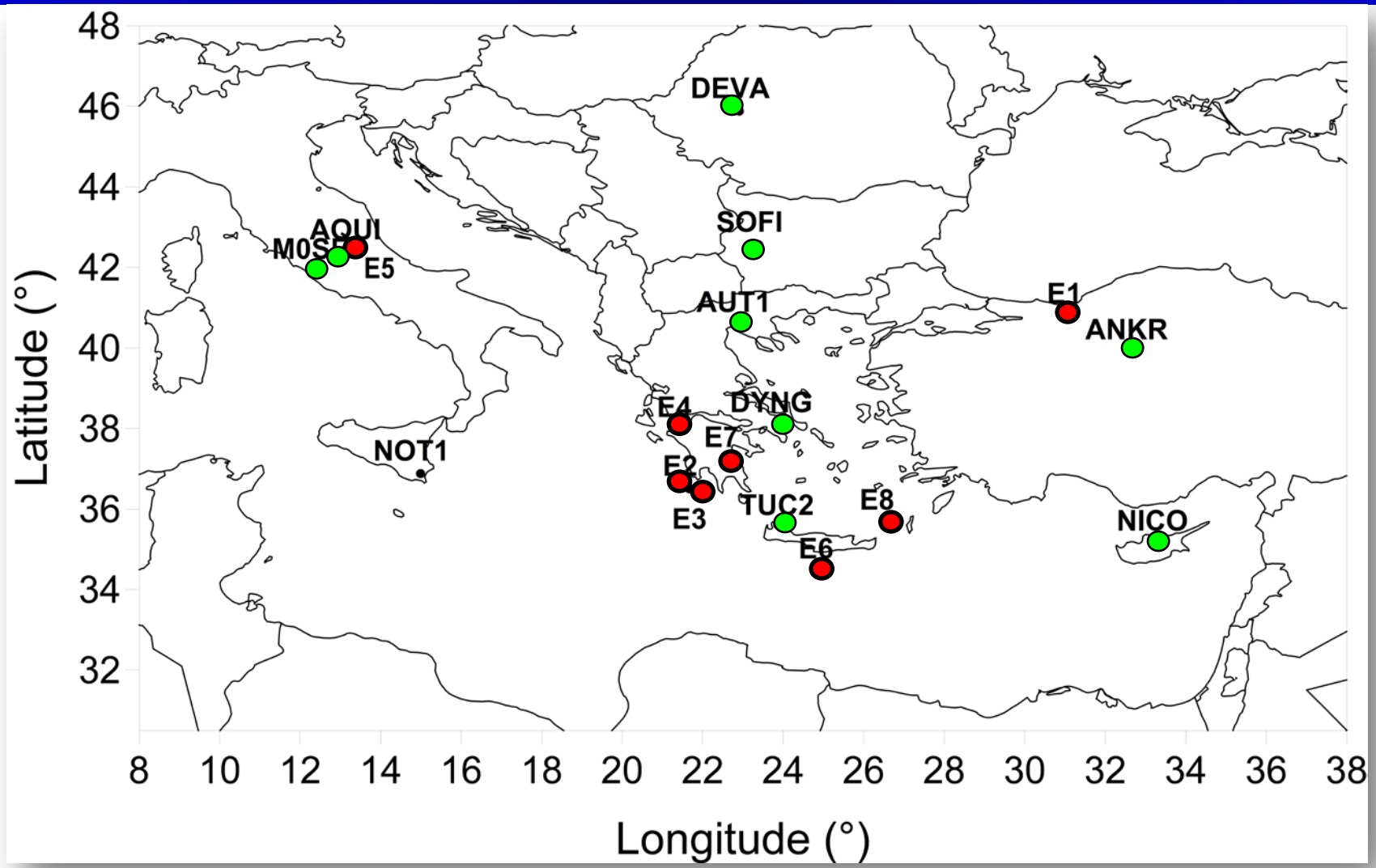
Pulinets S.A. and Boyarchuk K.A. (2004). Ionospheric precursors of earthquakes,Springer,Berlin

Data and methodology - *Seismic events*

No of Earthq.	Mw	Date time (UT)	R (km)	GNSS stations	GNSS stations	Lat (°)	Lon (°)	Depth (Km)	Region
				Inside preparation area	Outside preparation area				
E1	7.2	11/12/1999 16:57	1247	ANKR	NOT0, AQUI	40.78	31.21	10	western Turkey
E2	6.9	2/14/2008 10:09	927	TUC2	AQUI, NICO	36.50	21.67	29	southern Greece
E3	6.5	2/14/2008 12:08	624	TUC2	AQUI, NICO	36.35	21.86	28	southern Greece
E4	6.4	6/8/2008 12:25	565	AUT1, TUC2	ANKR	37.96	21.53	16	southern Greece
E5	6.3	4/6/2009 1:32	512	AQUI	AUT1, SOFI	42.33	13.33	8.8	central Italy
E6	6.2	6/15/2013 16:11	463	TUC2	ANKR, NICO, NOT1	34.45	25.04	10	Crete, Greece
E7	6.2	1/6/2008 5:14	463	TUC2	NICO, AQUI	37.22	22.69	75	southern Greece
E8	6	4/1/2011 13:29	380	TUC2	DEVA, M0SE	35.66	26.56	59.9	Crete, Greece

Earthquake catalogues of United States Geological Survey's (USGS) Earthquake Hazards Program

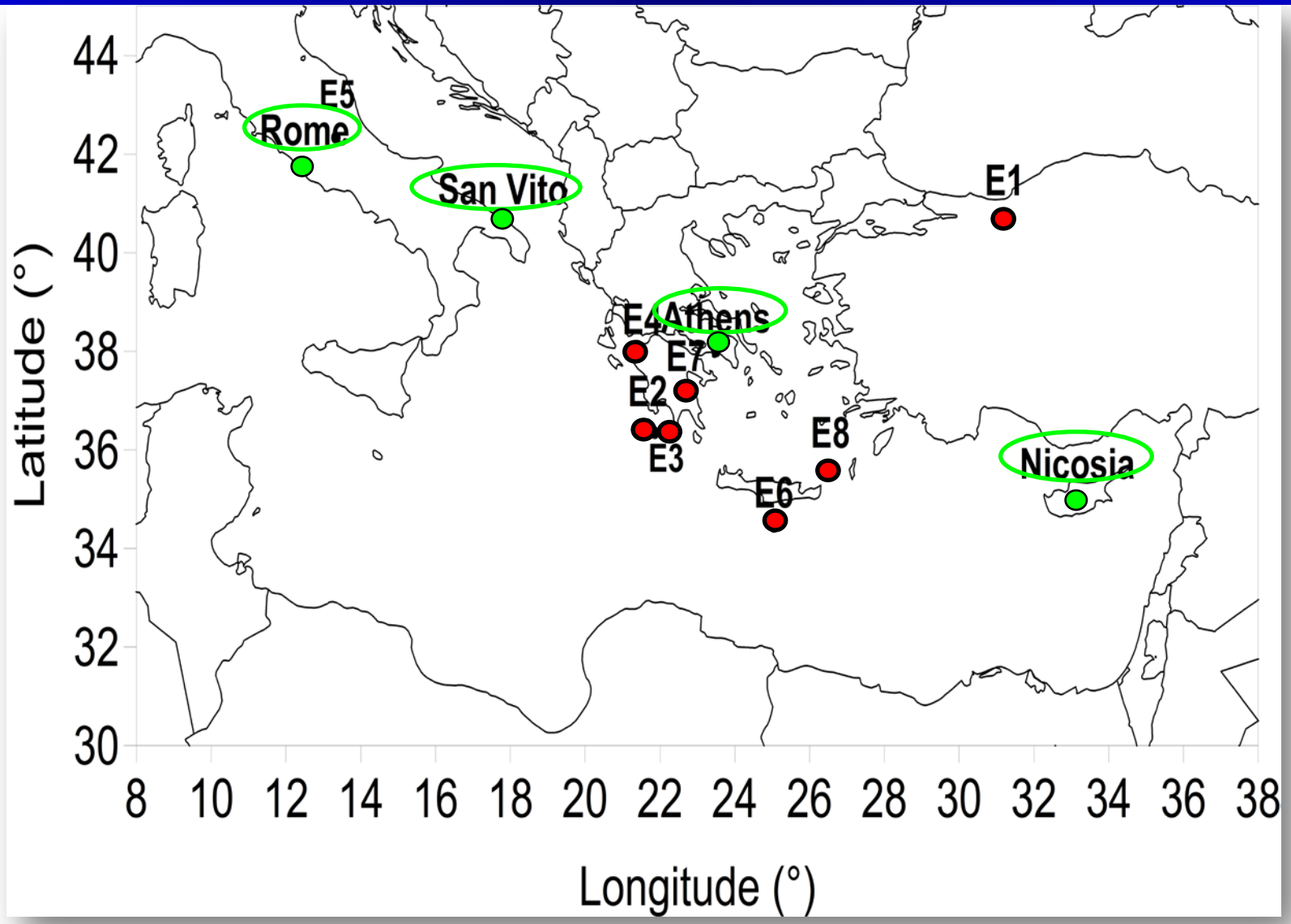
Data and methodology - GNSS stations



- Map of selected European GNSS receivers (**green** dots) from:
EUREF Permanent Network (EPN) http://www.epncb.oma.be/index.php

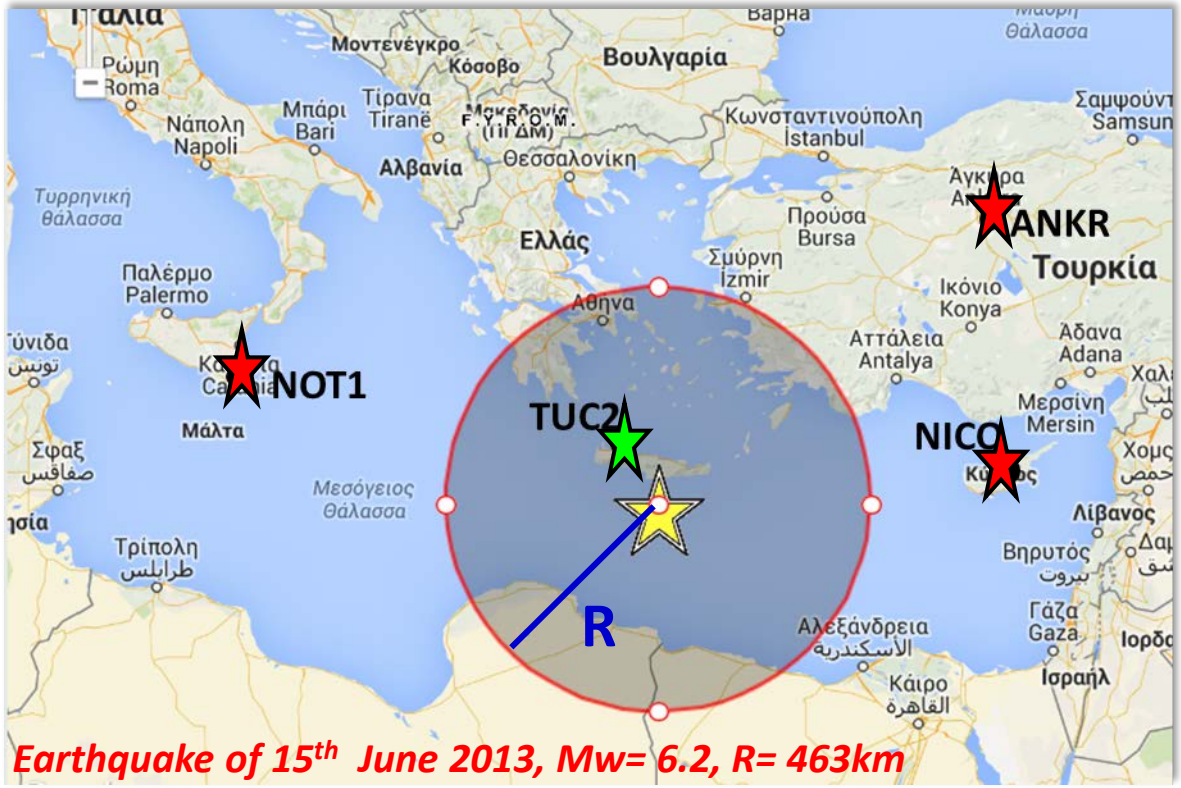
- The epicenters of the examined earthquakes E1, E2, E3, E4, E5, E6, E7, and E8 (**red** dots)

Data and methodology - Ionosonde stations



- Map of selected **Ionosonde** stations at Athens, Nicosia, Rome, San Vito (**green** circles)
- The epicenters of the examined earthquakes E1, E2, E3, E4, E5, E6, E7, and E8 (**red** dots)

Data and methodology - Cross-Correlation Technique



Control stations

Sensor stations

Epicenter

R Radius of preparation area

$$R = 10^{0.43M} \text{ (km)}$$

M= the earthquake magnitude

- **DATA:** - vTEC from GNSS stations with 5 min. resolution
  - foF2 from Ionosonde stations, manually scaled and with 1 hr resolution

- We calculated the daily cross- correlation coefficient between time series of sensor and control stations. The cross-correlation coefficient for the 2 stations is expected to be very high. In case of earthquake, this short-term cross-correlation coefficient may decrease

- We also calculated the daily auto-correlation coefficient for each station, by assessing the coefficient between one day and the next day. Any drop of the coefficient detected at the sensor station will be expected to be reflected to the cross-correlation coefficient only if it is induced by seismic activity, while the drops of auto-correlation coefficient caused by geomagnetic storms are not be reflected.

Data and methodology - Spectral Analysis

- **DATA: Differential sTEC** (difference of sTEC measurement between two successive satellite epochs)

- sTEC was estimated using an algorithm developed by Buldan Muslim *(Indonesian National Institute of Aeroautics and Space, LAPAN)*

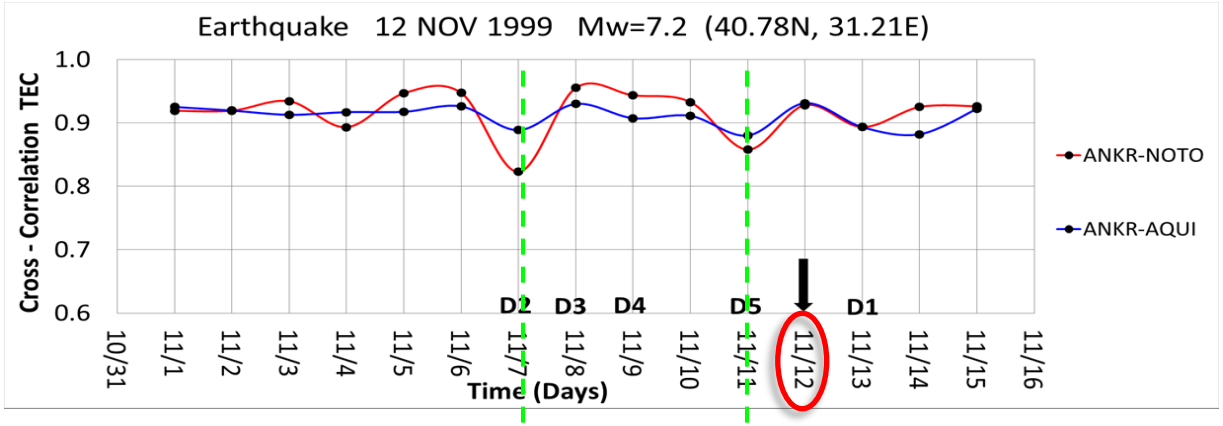
- Since we are interested only for possible large-scale ionospheric precursors induced from anomalous electric field or AGWs caused by gas emissions several days prior to earthquakes we performed spectral analysis in order to detect high fluctuations of differential sTEC with **period of oscillation up to 30 minutes**

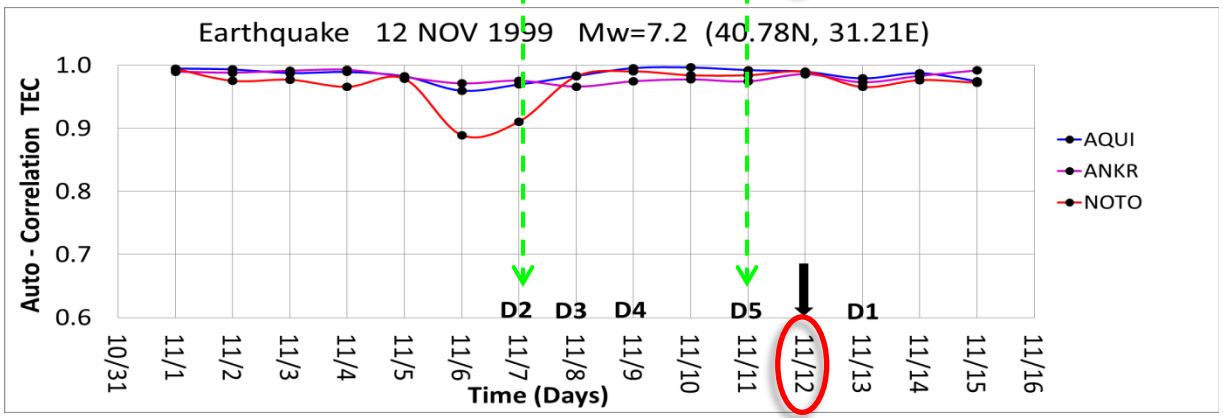
- We estimated

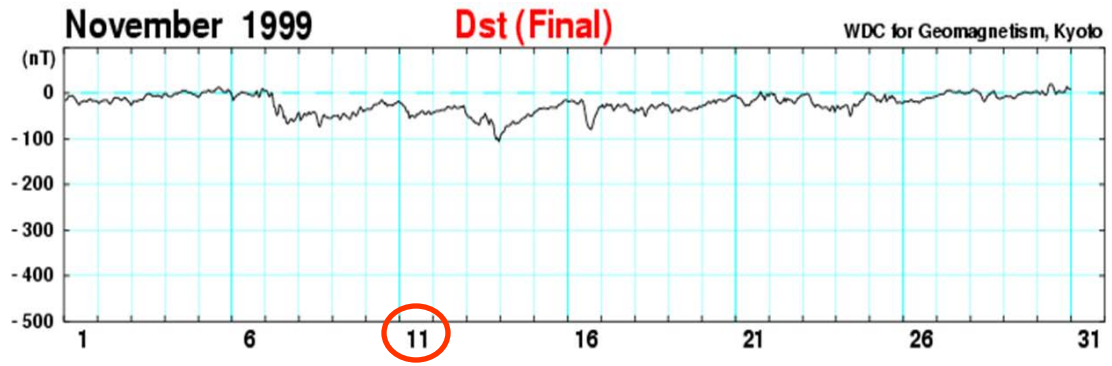
a) fluctuations of differential slant TEC prior, during and one day after the earthquake

b) power spectrum of a normalized amplitude of fluctuations, which is proportional to the actual amplitude

Results - Cross-correlation technique - 12th Nov 1999



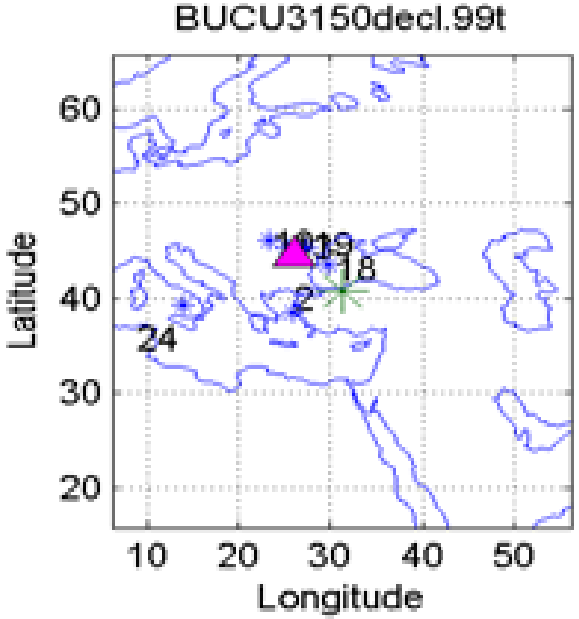




- **Drops of cross-correlation R at 7th and 11th Nov. occur during moderate geom. Storm. Therefore, we cannot be sure if drop is due to storm or earthquake. Spectral analysis shows high fluctuations of dTEC with period 15min at the same dates.**
- **We observe the auto-correlation for NOT to decrease instead of ANKR.**

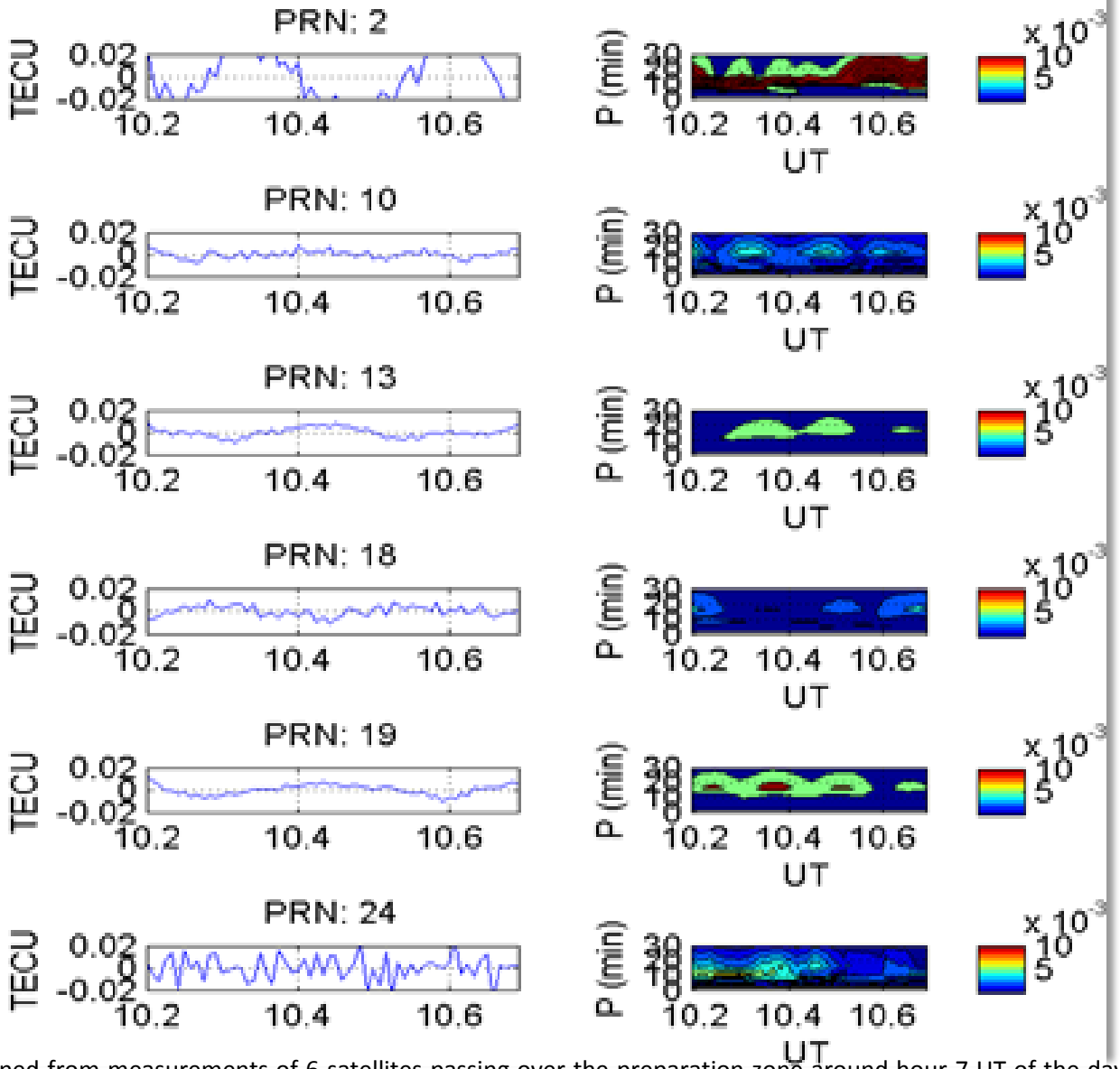
Geomagnetically disturbed days are denoted with Di (i=1, 2, 3, 4, 5) following the geomagnetic bulletins provided by the National Geophysical Data Center (NGDC) (https://www.ngdc.noaa.gov/). The five most active days from the most (D1) to least disturbed (D5) are shown

Results - Spectral Analysis - 12th Nov 1999



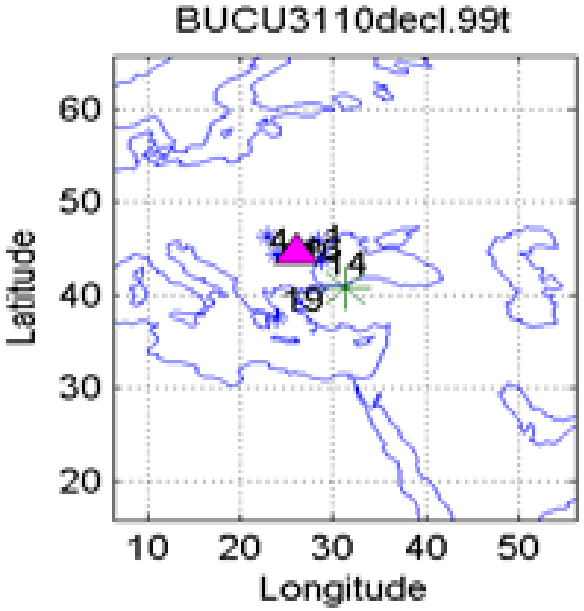
Mw = 7.2
R = 1247 km
16:57 UT

11th Nov. 1999
Day of drop of R



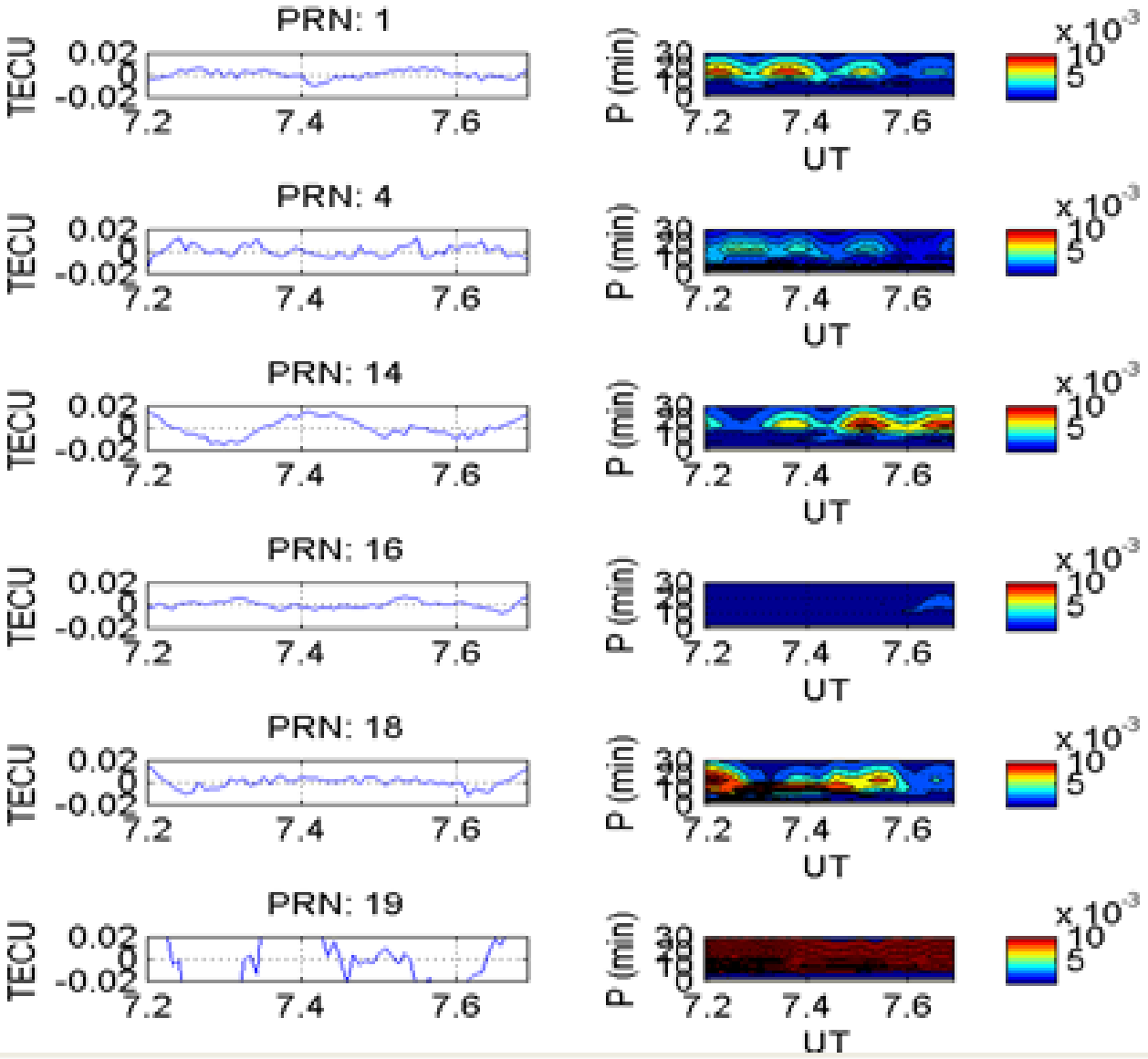
Fluctuations of differential TEC (middle panels) obtained from measurements of 6 satellites passing over the preparation zone around hour 7 UT of the day 7th November 1999 **were large drop of cross-correlation coefficien**t was found. The power spectrum of the normalized amplitude is also shown (right panels). Map shows the number and position of ionospheric pierce point (IPP) of each satellite that is observed from Nicosia GPS receiver (blue asterisks), the position of the GPS receiver (pink triangle) at the same date, and the epicenter (green asterisk) of the earthquake at 12th November 1999.

Results - Spectral Analysis - 12th Nov 1999



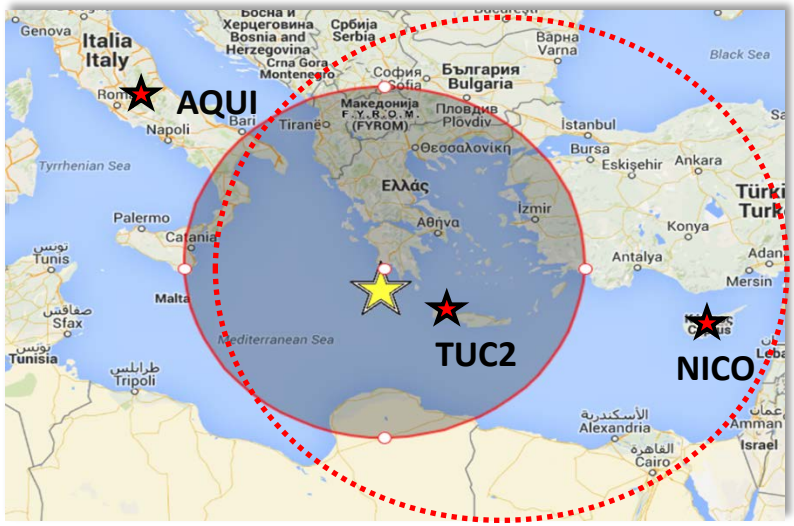
Mw = 7.2
R = 1247 km
16:57 UT

7th Nov. 1999
Day of drop of R



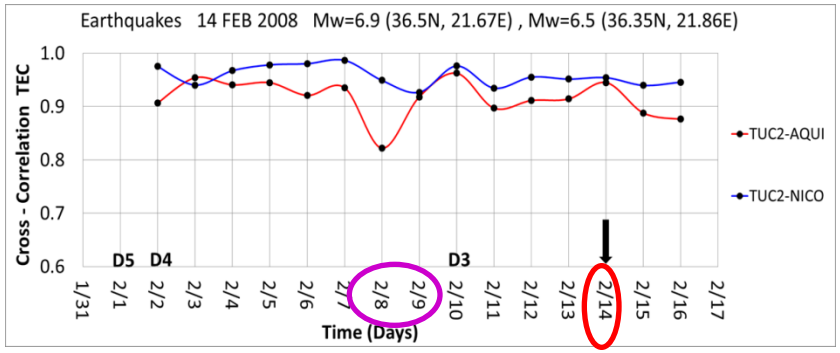
Fluctuations of differential TEC (middle panels) obtained from measurements of 6 satellites passing over the preparation zone around hour 7 UT of the day 11th November 1999 **were large drop of cross-correlation coefficien**t was found. The power spectrum of the normalized amplitude is also shown (right panels). Map shows the number and position of satellites (blue asterisks), the position of the GPS receiver (pink triangle) at the same date, and the epicenter (green asterisk) of the earthquake at 12th November 1999.

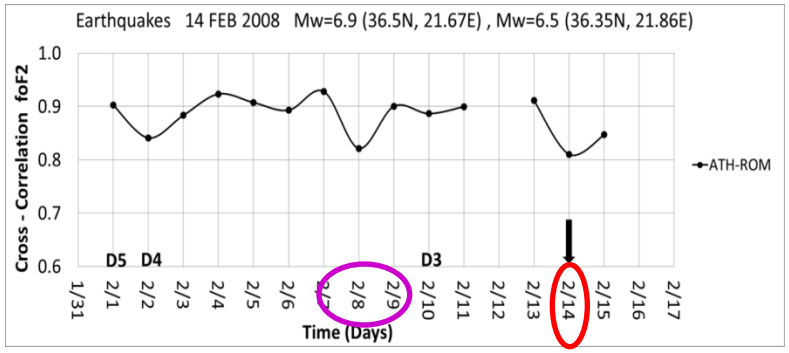
Results - Cross-correlation technique – 14th Feb 2008

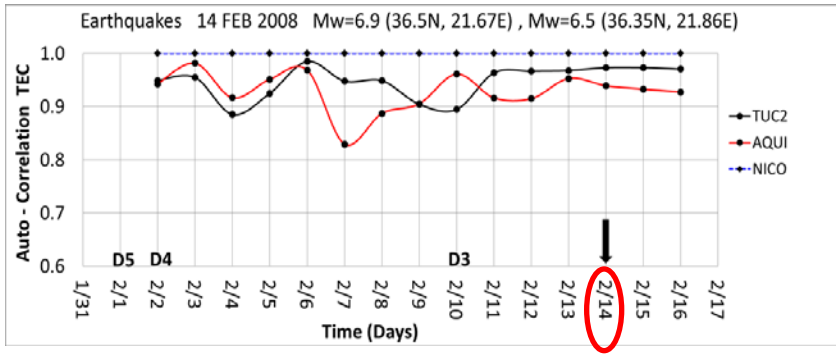


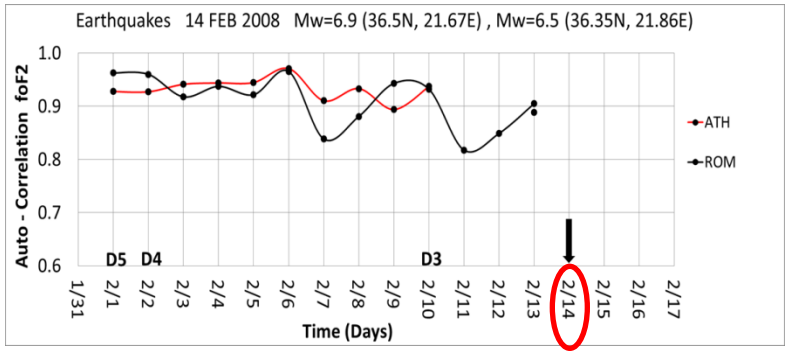
Mw=6.9	2/14/2008 10:09 UT	R = 927 km (dotted cycle)
Mw=6.5	2/14/2008 12:08 UT	R = 624 km (solid cycle)

- We notice drop of cross-correl. coef. R at 8-9 Feb. both at TEC and foF2. The same dates spectral analysis shows high fluctuations of dTEC with period around 15-20 min.
- The drops of auto-correl coeff. are reflected on cross-correl only if they are due to earthquake
- The high drop of auto-correl. coef. at 7th Feb. at AQUI is possibly due to missing values of TEC data

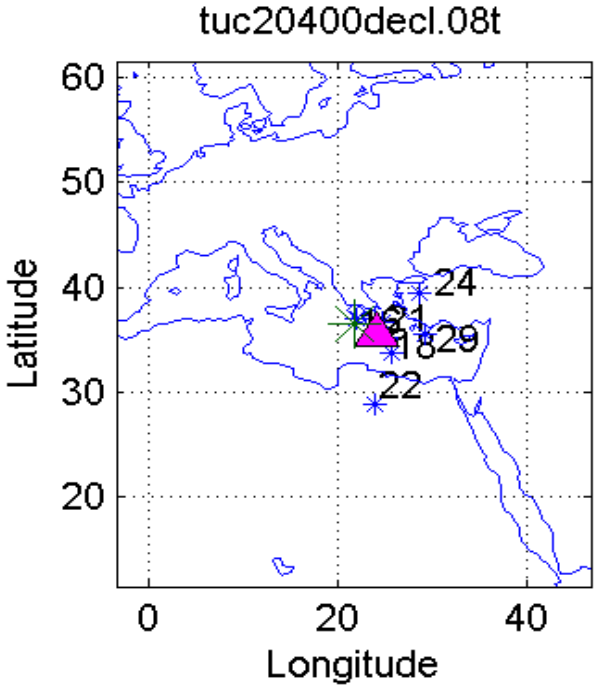


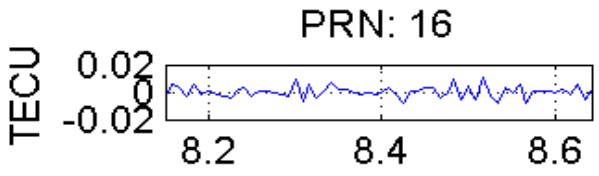


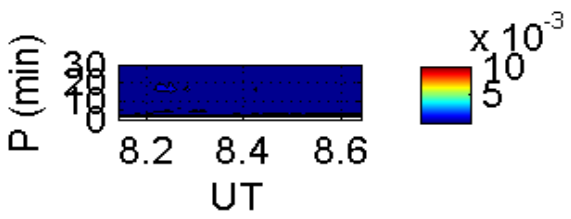


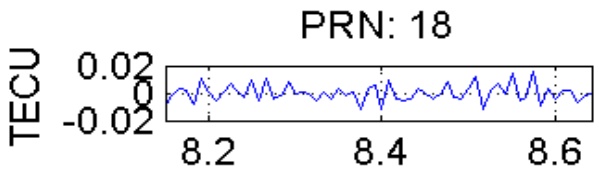


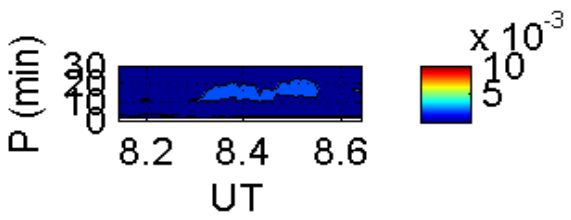
Results - Spectral Analysis – 14th Feb 2008

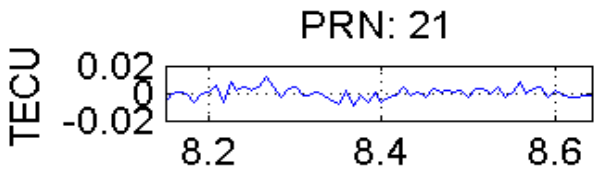


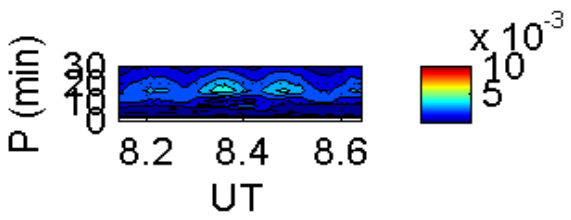


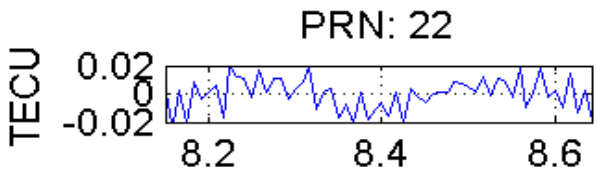


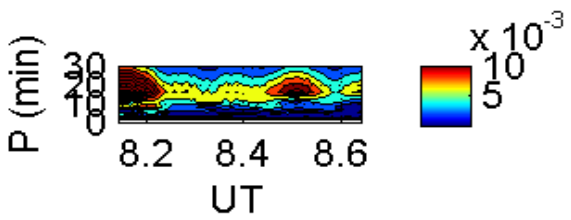


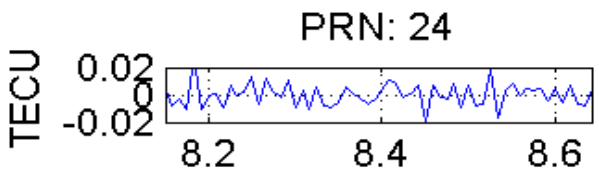


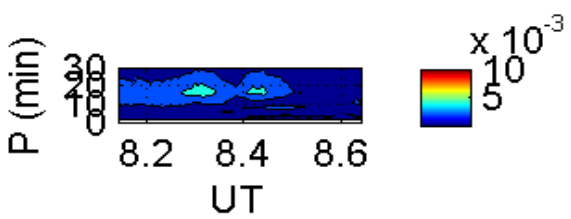


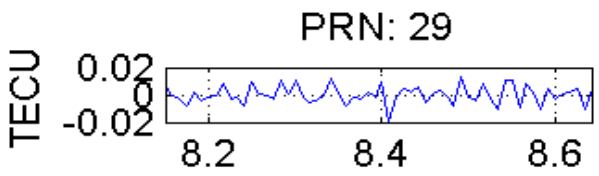


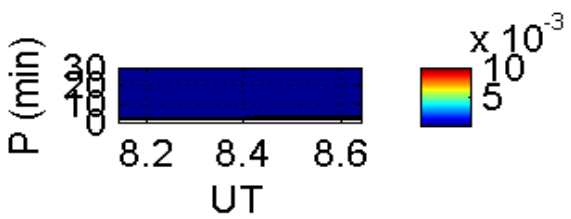










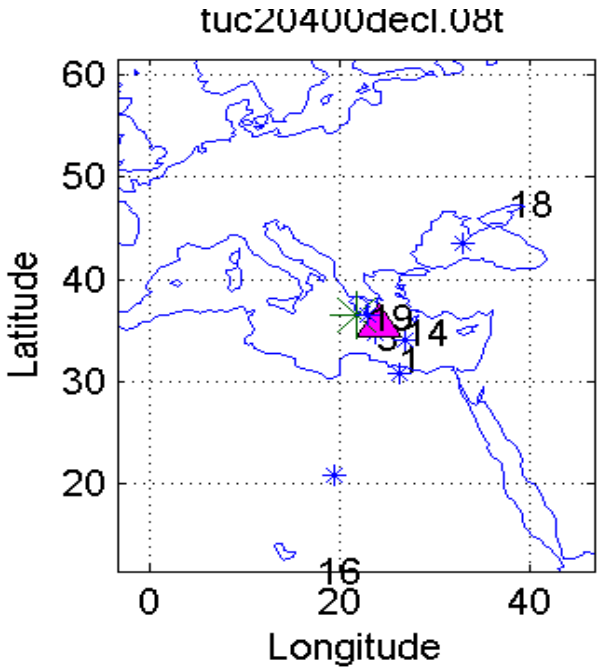


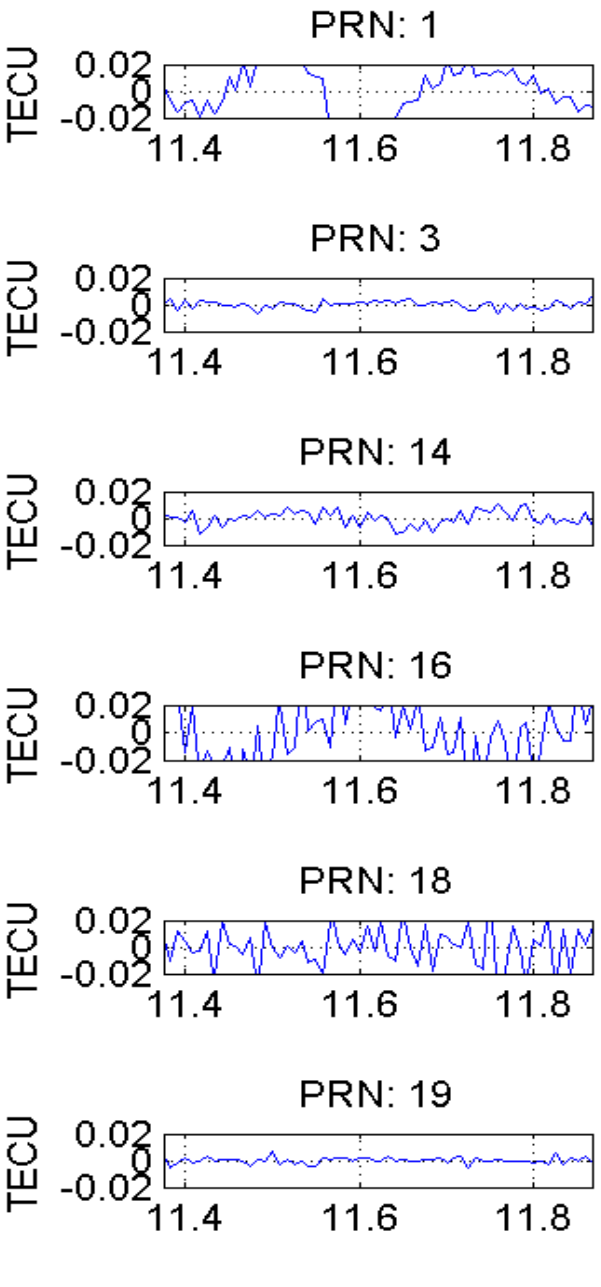
9th Feb 2008
Day of drop of R

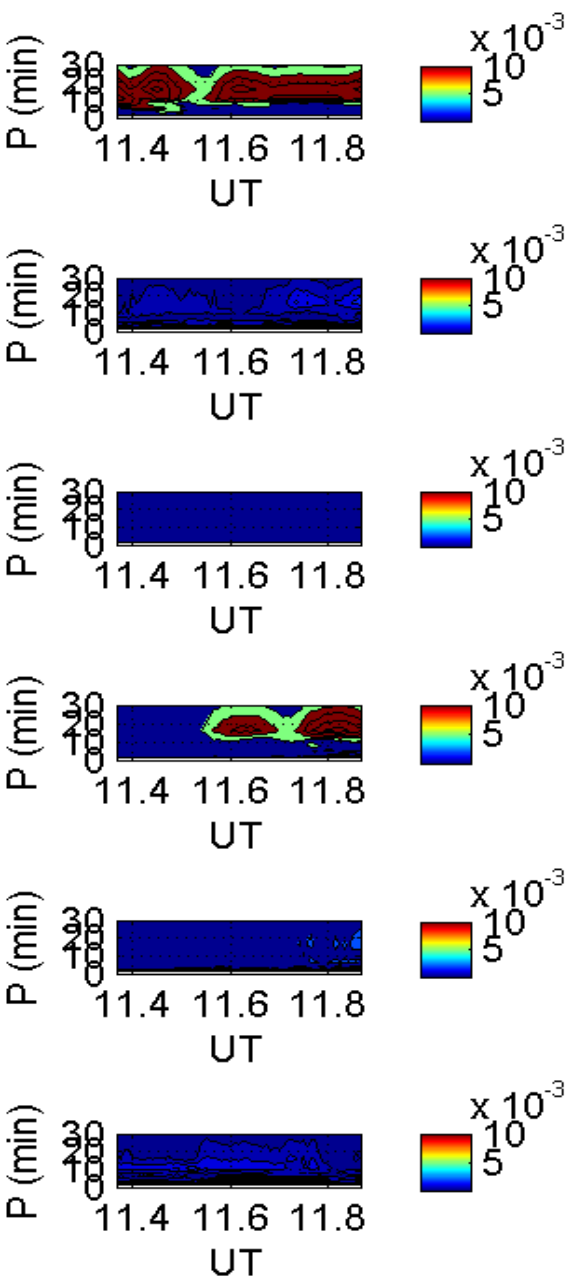
Mw=6.9 10:09 UT R = 927 km

Mw=6.5 12:08 UT R = 624 km

Results - Spectral Analysis – 14th Feb 2008







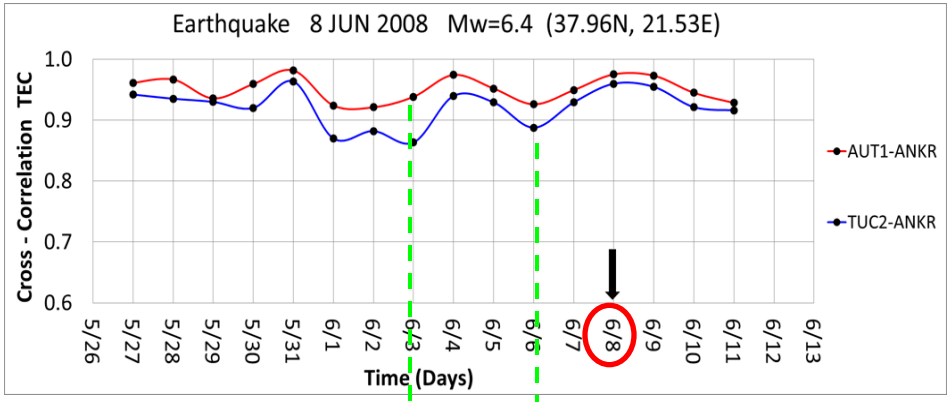
9th Feb 2008
Day of drop of R

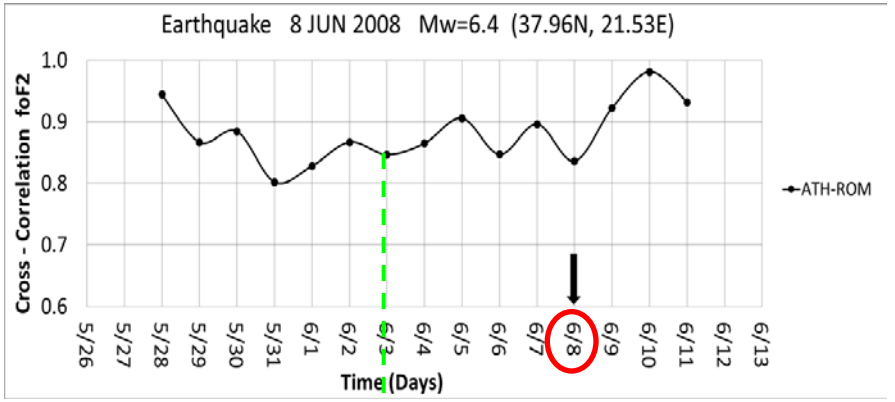
Mw=6.9	10:09 UT	R = 927 km
Mw=6.5	12:08 UT	R = 624 km

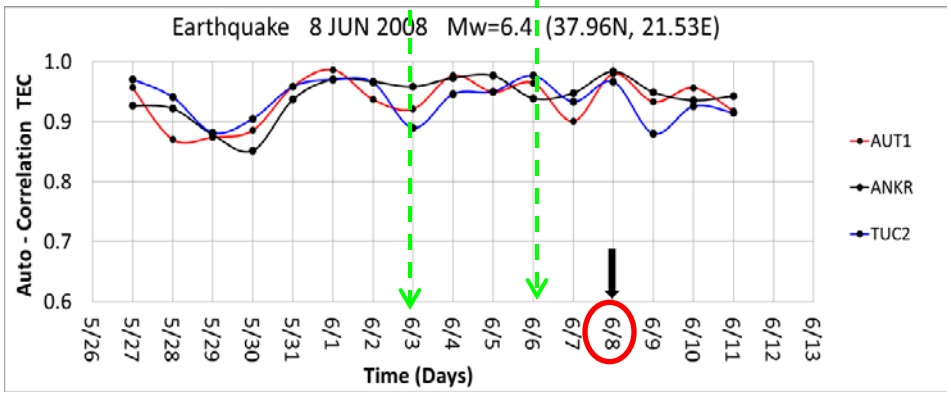
Results - Cross-correlation technique - 8th Jun 2008

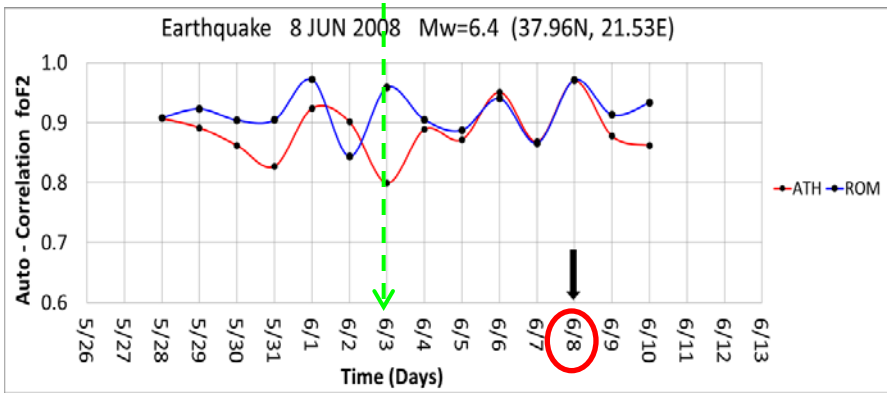
8th Jun 2008
Mw = 6.4 12:25 UT R = 565 km

- At 2-3 June we observe drops of cross and auto correl. Coef. both at TEC and foF2 which can be due to earthquake. At the same dates spectral analysis shows high fluctuations of dTEC.
- There is no significant drop of TEC auto correl. coef. of sensor stations at 1st and 6th June, however, a small drop of cross-correl. coef. is noted.
- Results of foF2 correl. anal. are unreliable since 35% of foF2 values was missing both at Athens and Rome

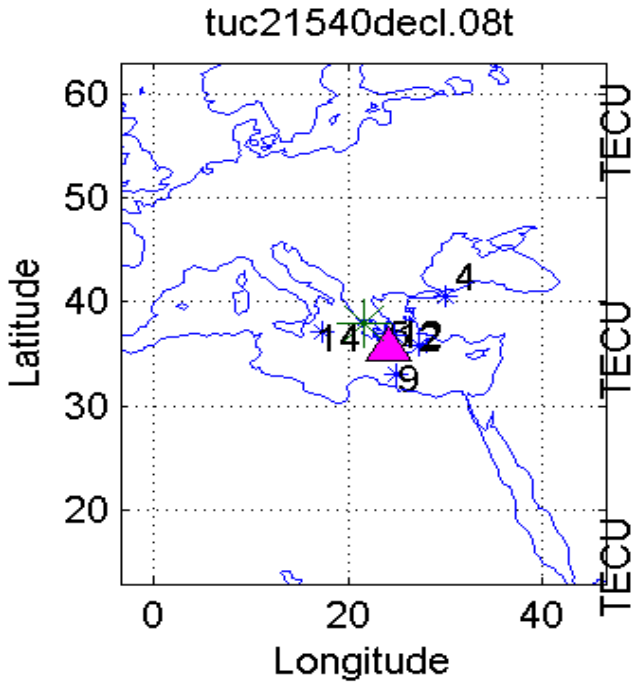


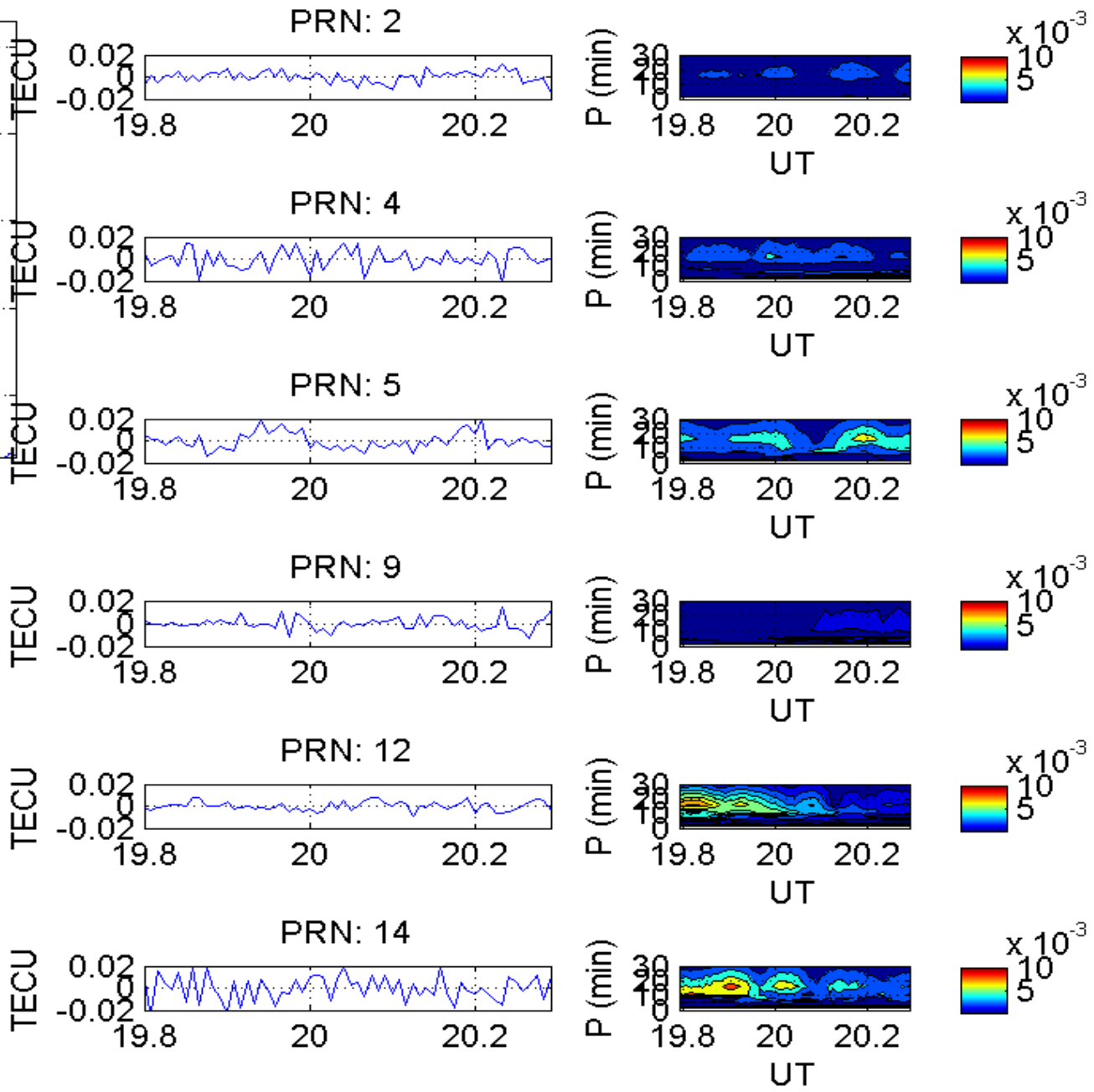






Results - Spectral Analysis - 8th Jun 2008

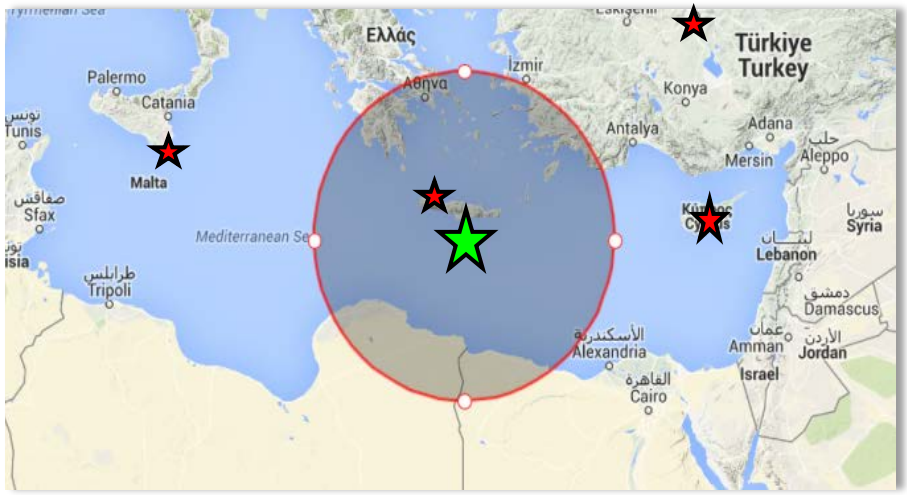




Mw = 6.4
R = 565 km
12:25 UT

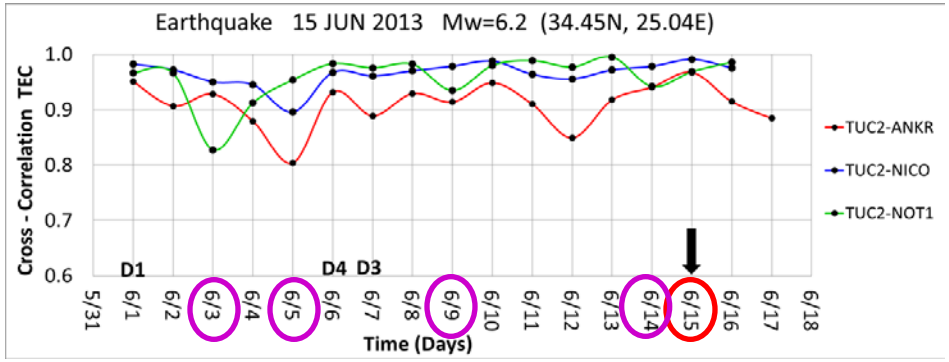
2nd June 2008
Day of drop of R

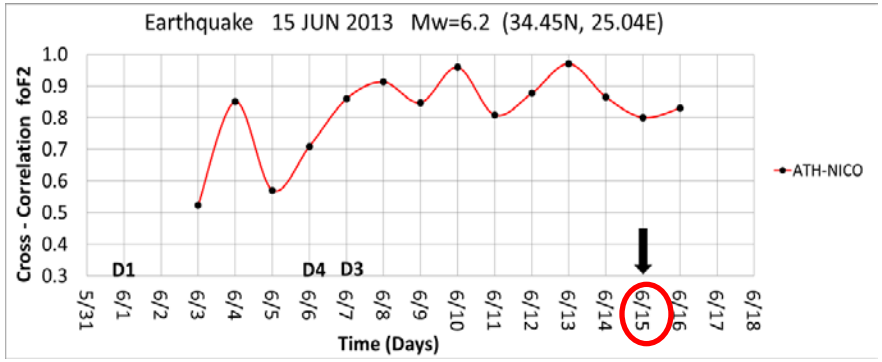
Results - Cross-correlation technique - 15th Jun 2013

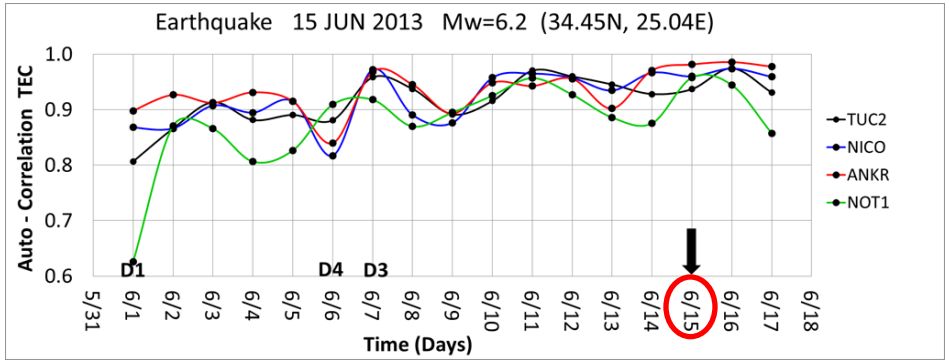


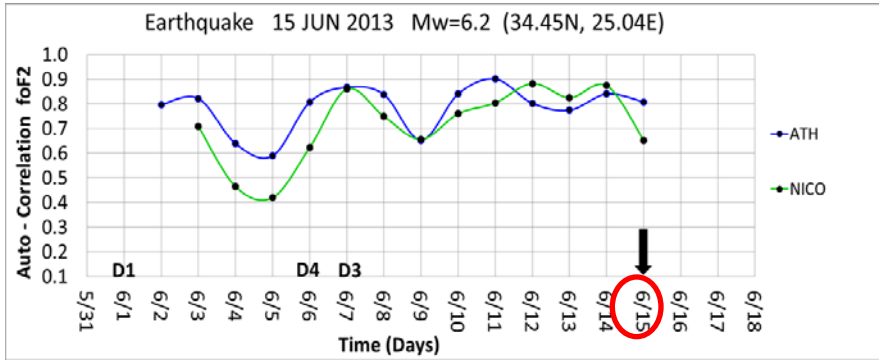
15th Jun 2013
Mw = 6.2 16:11 UT R = 463 km

- **At 3, 5, 9 and 14 June we observe drops of auto correl coef of the sensor st. which are reflected on cross correl. coef.**
- **The results of foF2 at 3 and 11 June are unreliable, as 20% of foF2 values were missing.**

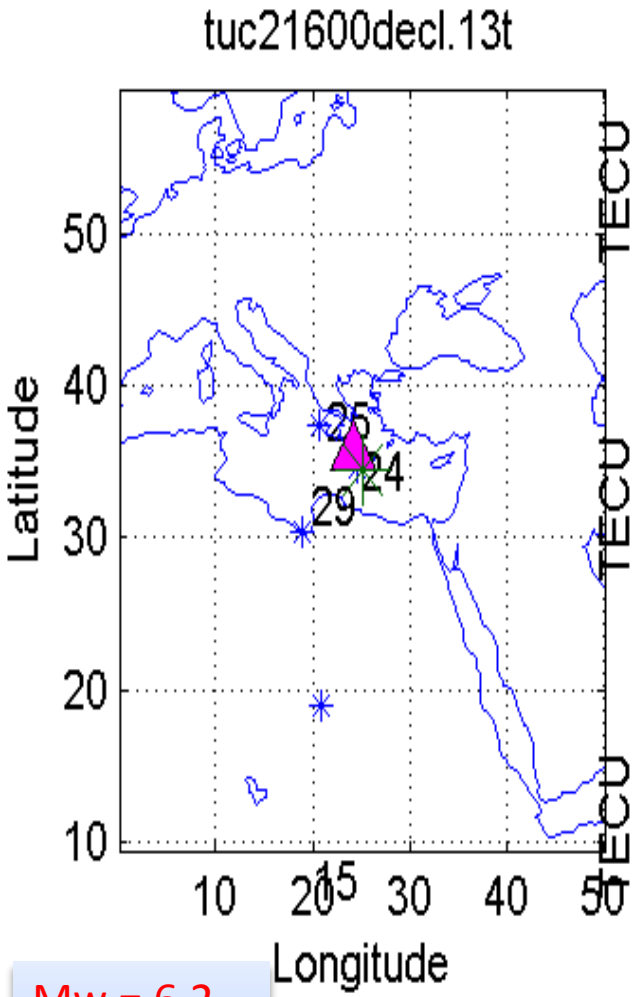


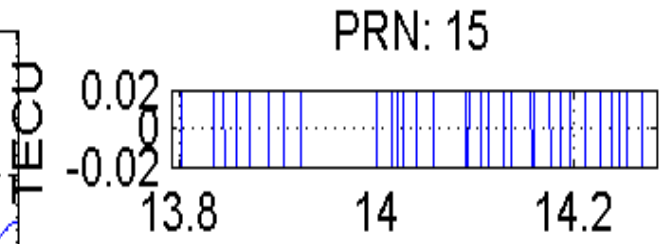


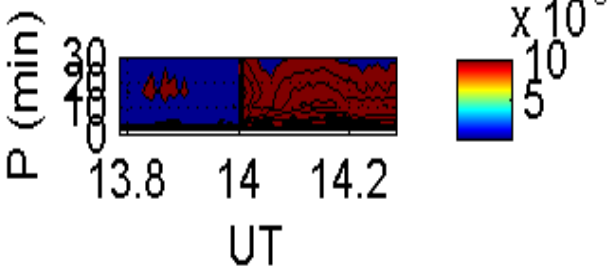


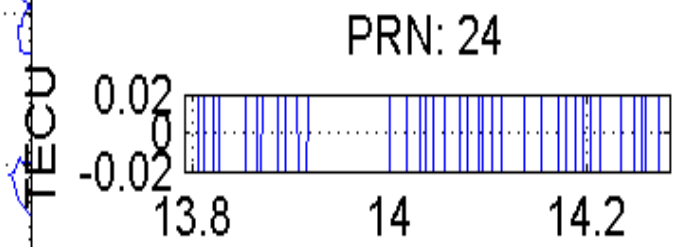


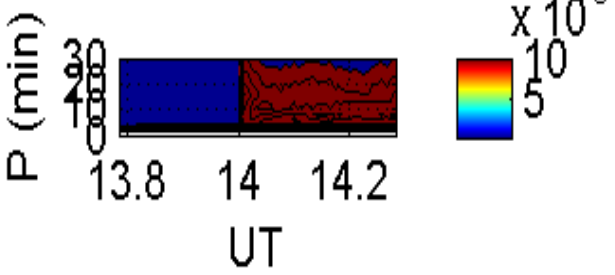
Results - Spectral Analysis - 15th Jun 2013

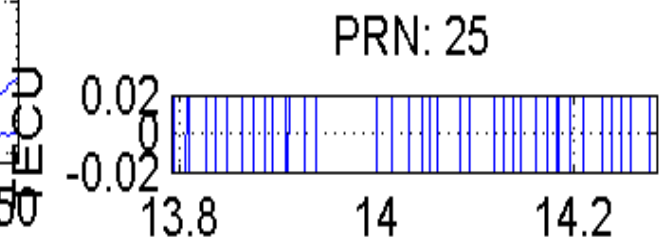


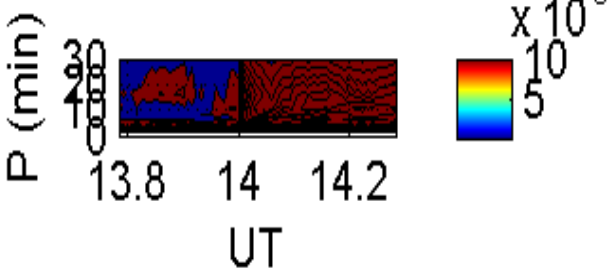


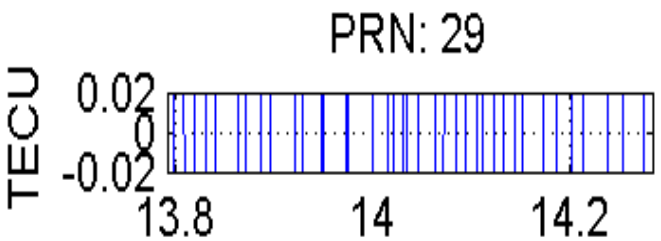


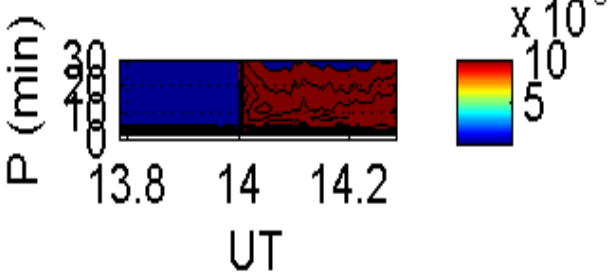








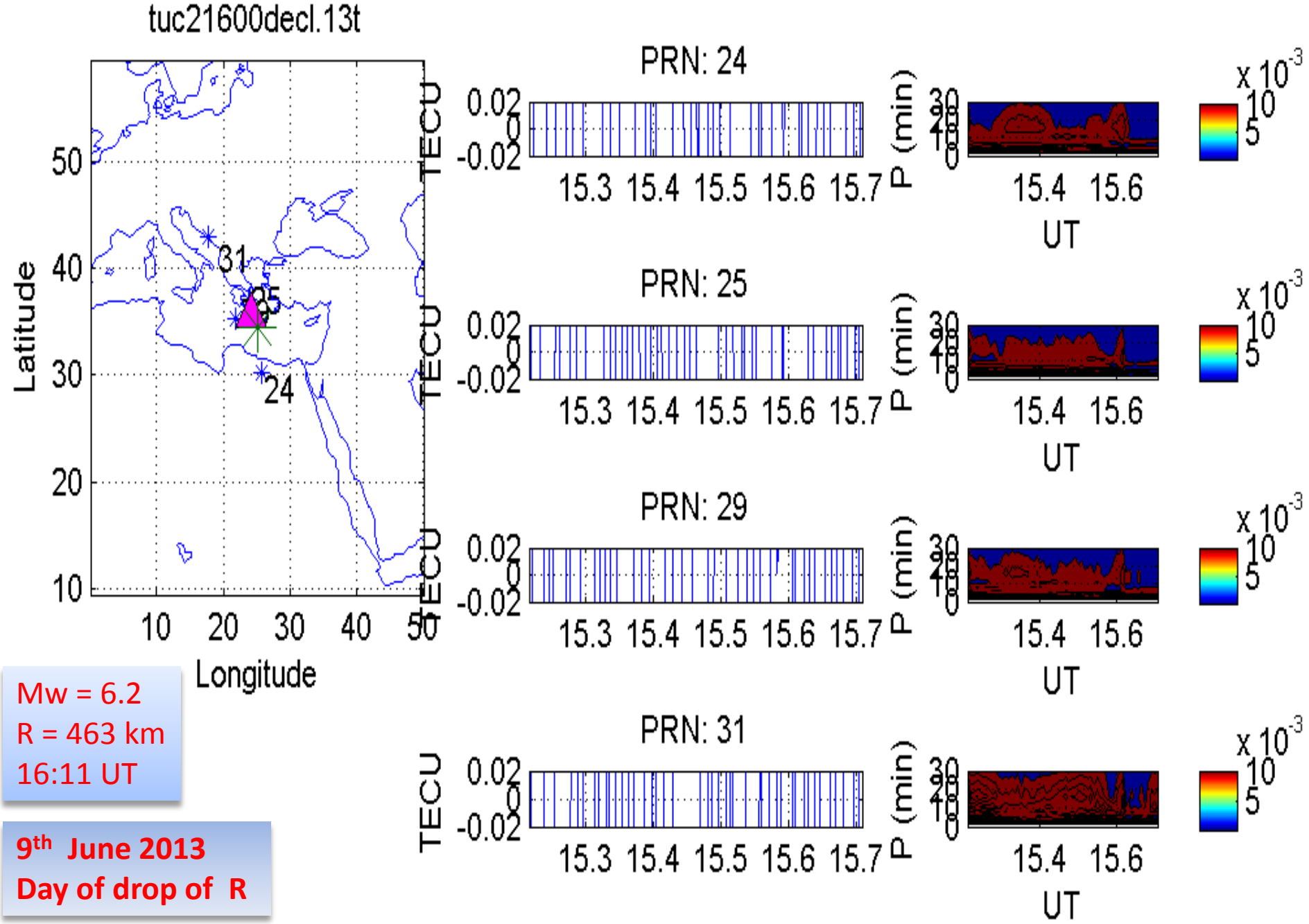




Mw = 6.2
R = 463 km
16:11 UT

9th June 2013
Day of drop of R

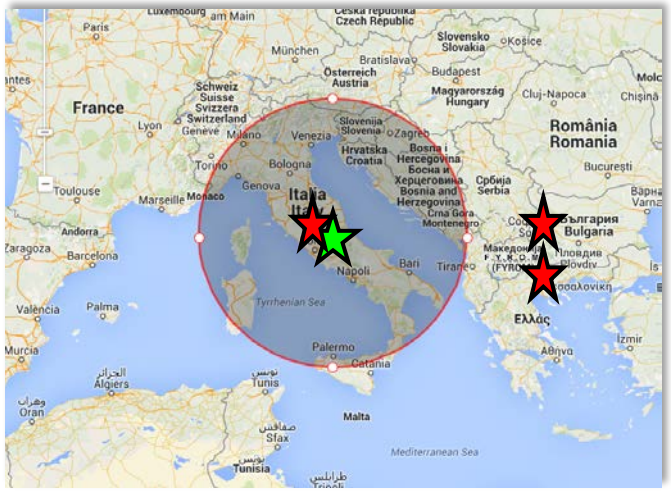
Results - Spectral Analysis - 15th Jun 2013



Mw = 6.2
R = 463 km
16:11 UT

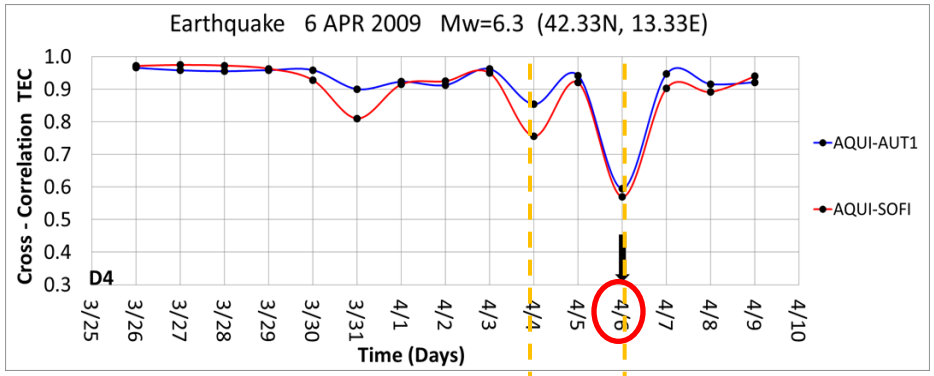
9th June 2013
Day of drop of R

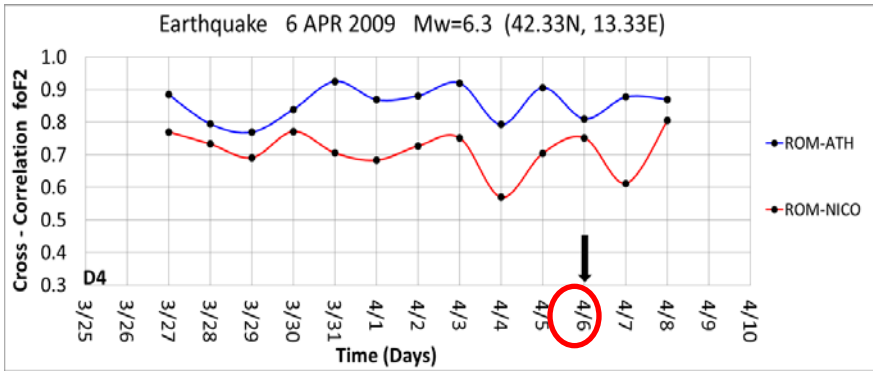
Results - Cross-correlation technique - 6th Apr 2009

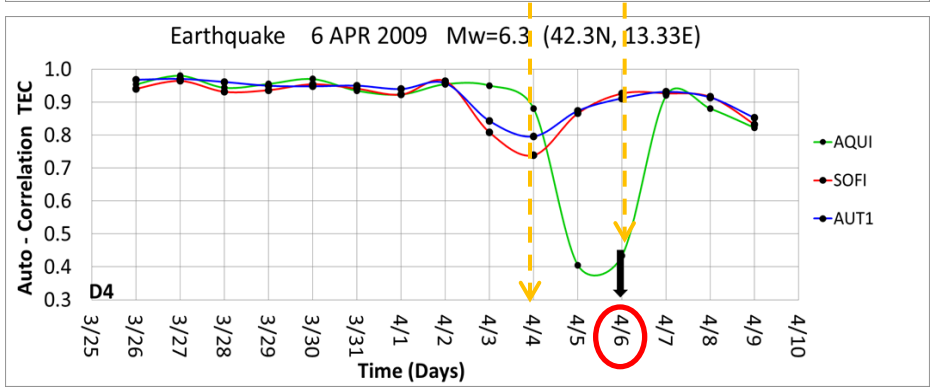


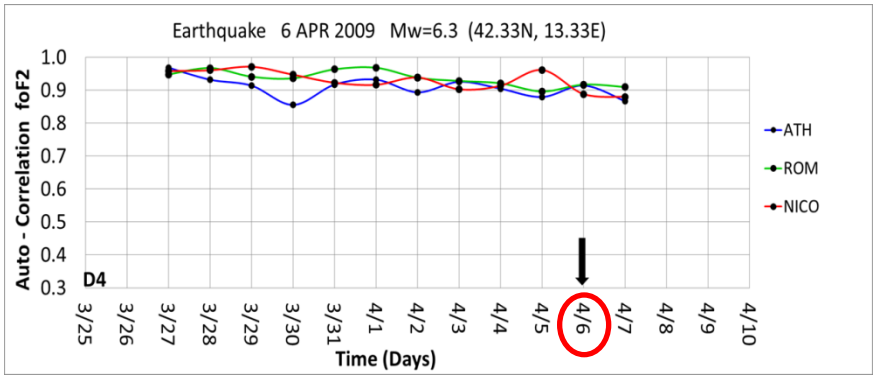
6th Apr 2009
Mw = 6.3 1:32 UT R = 512 km

- High drop of auto (sensor st.) and cross correl coef of TEC the day of the earthquake
- The drop at 4 April is seen both at foF2 and TEC cros—correl anal plots
- At 31st March, 30% of TEC values was missing at Sofi st.

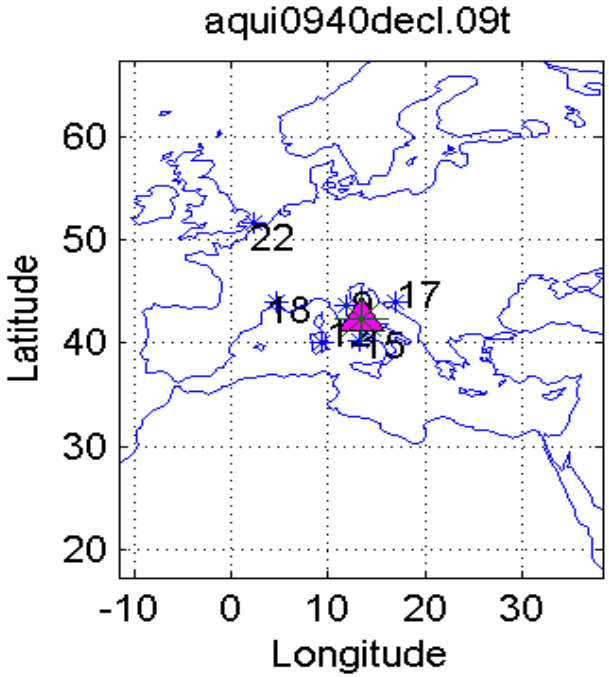


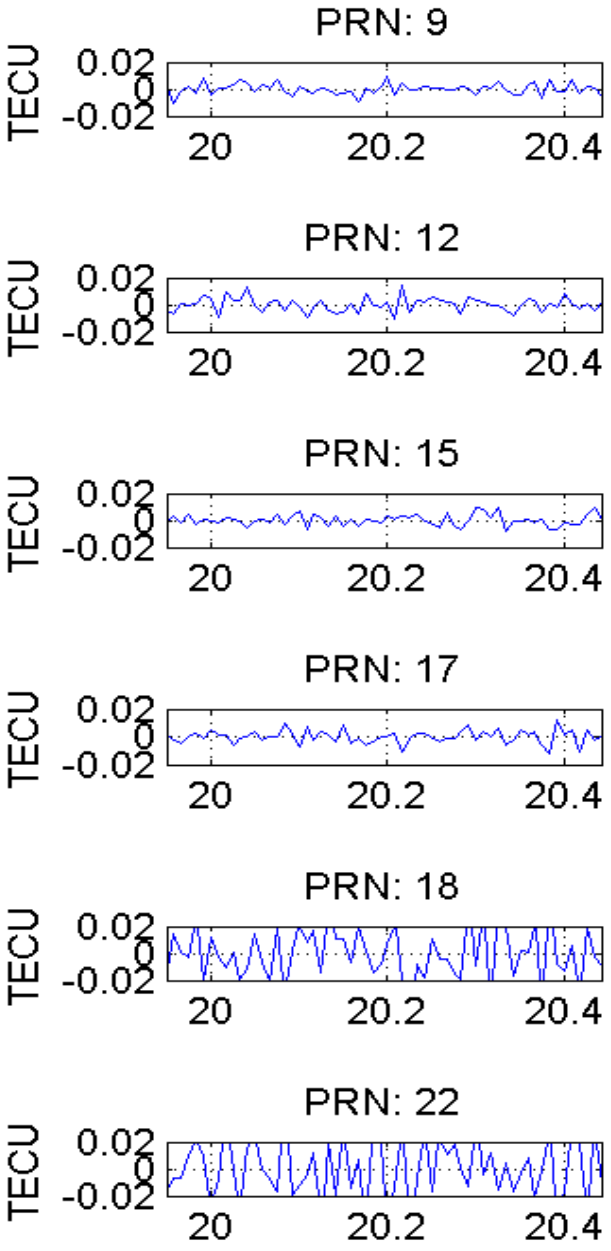


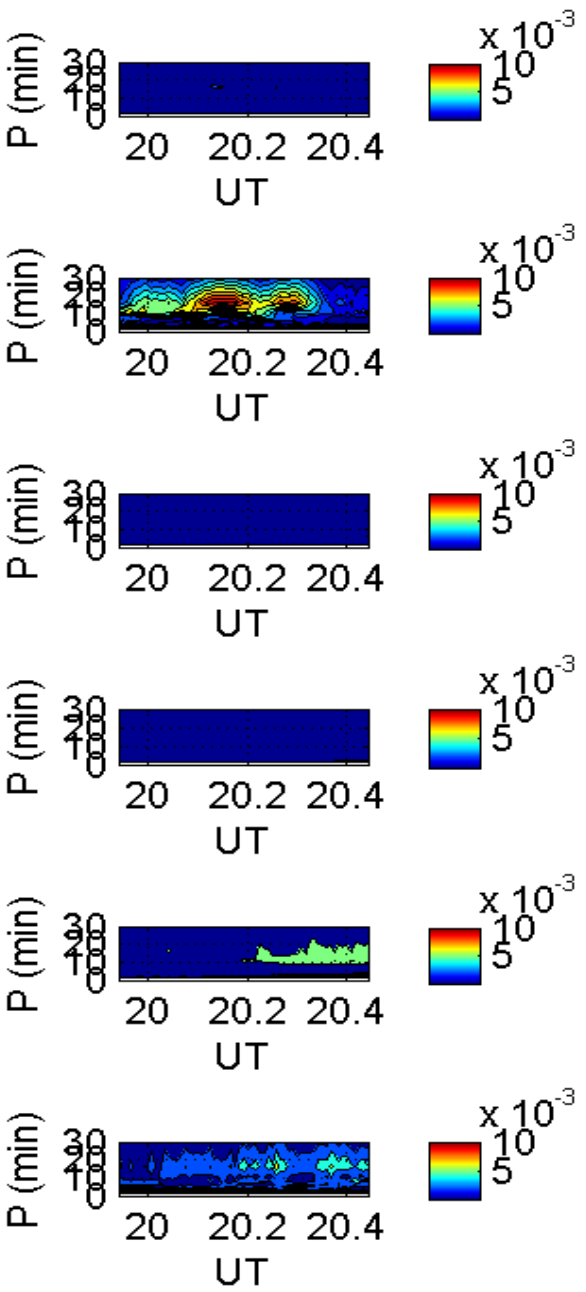




Results - Spectral Analysis - 6th Apr 2009



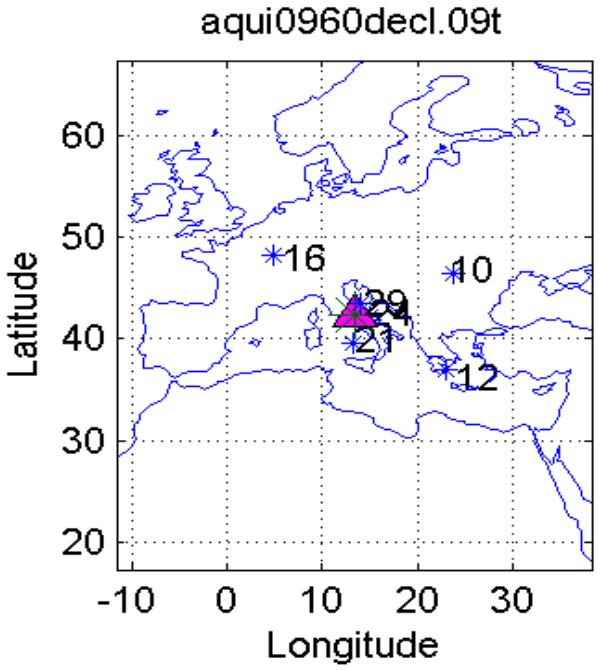




Mw = 6.3
R = 512 km
01:32 UT

4th April 2009
Day of drop of R

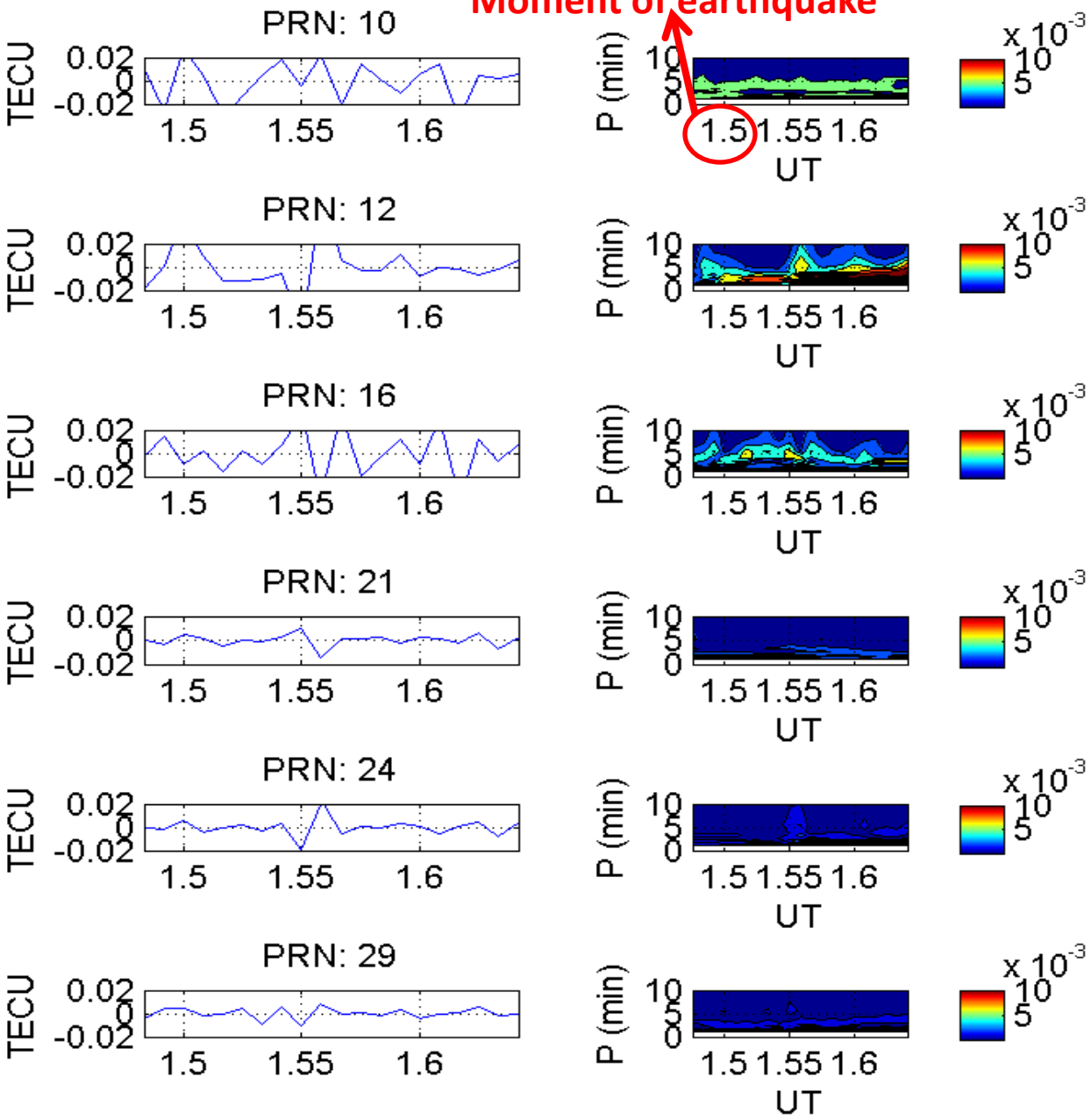
Results - Spectral Analysis - 6th Apr 2009



Mw = 6.3
R = 512 km
01:32 UT

p=10min
***acoustic waves**
after earthquake

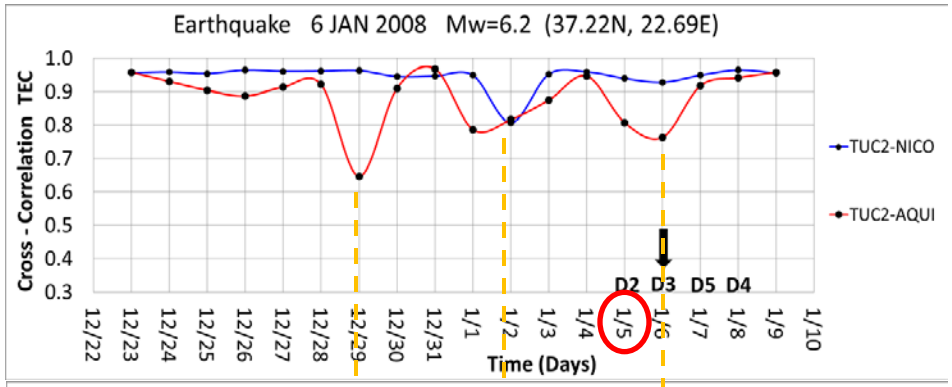
Moment of earthquake

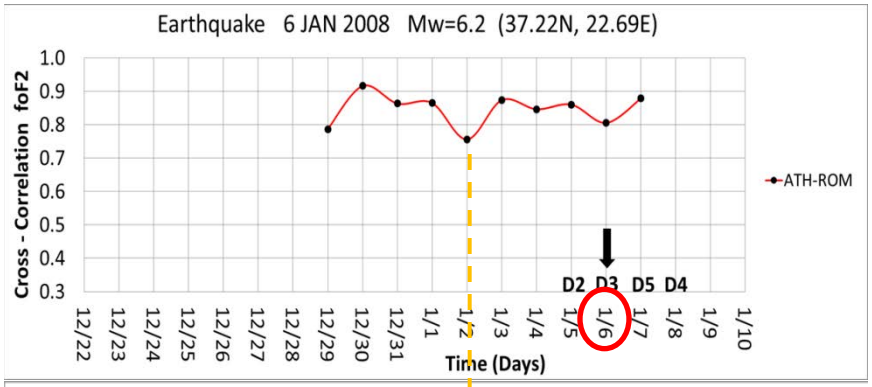


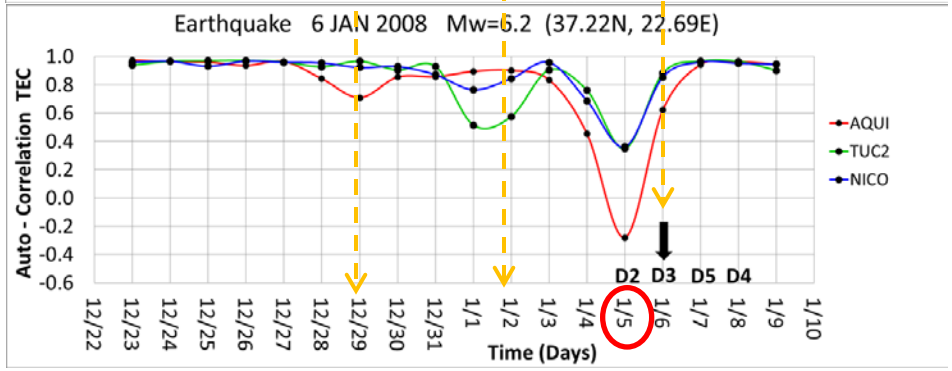
Results - Cross-correlation technique - 6th Jan 2008

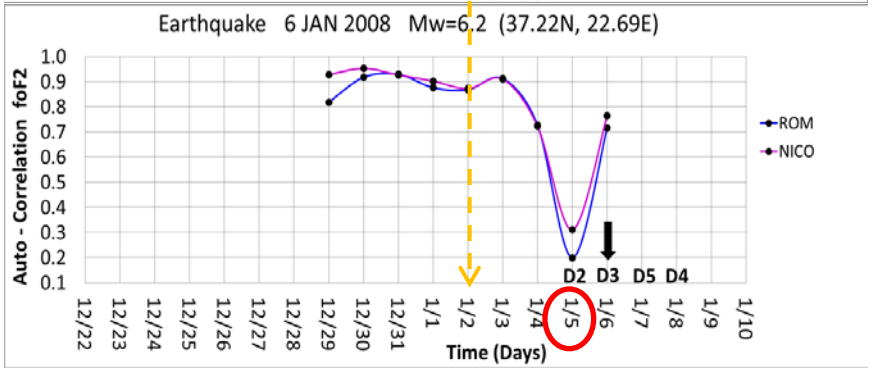
6th Jan 2008
Mw = 6.2 5:14 UT R = 463 km

- At 2nd Jan the drop of auto-correl coef of sensor st. TUC2 is reflected on cross-correl analysis.
- The drops one day before and the day of earthquake occur during geomagnetically active period, however, the spectral analysis for these days shows high fluctuations of dTEC with period of oscillations around 15 min.

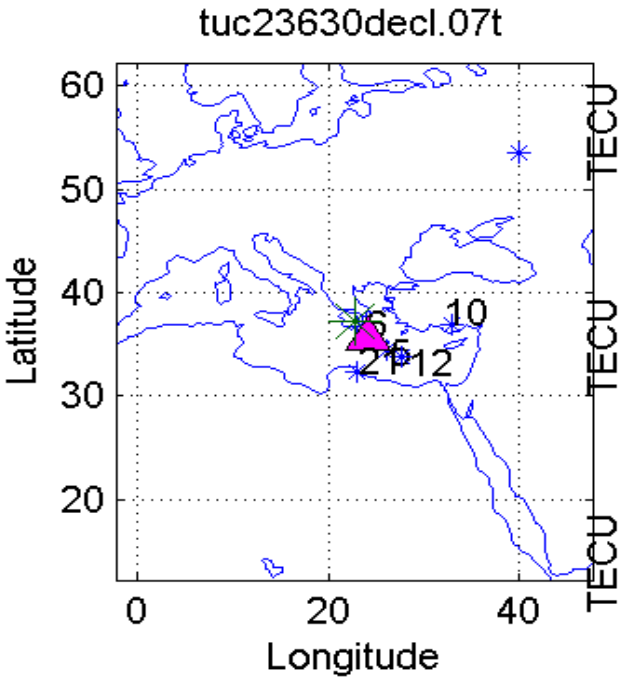






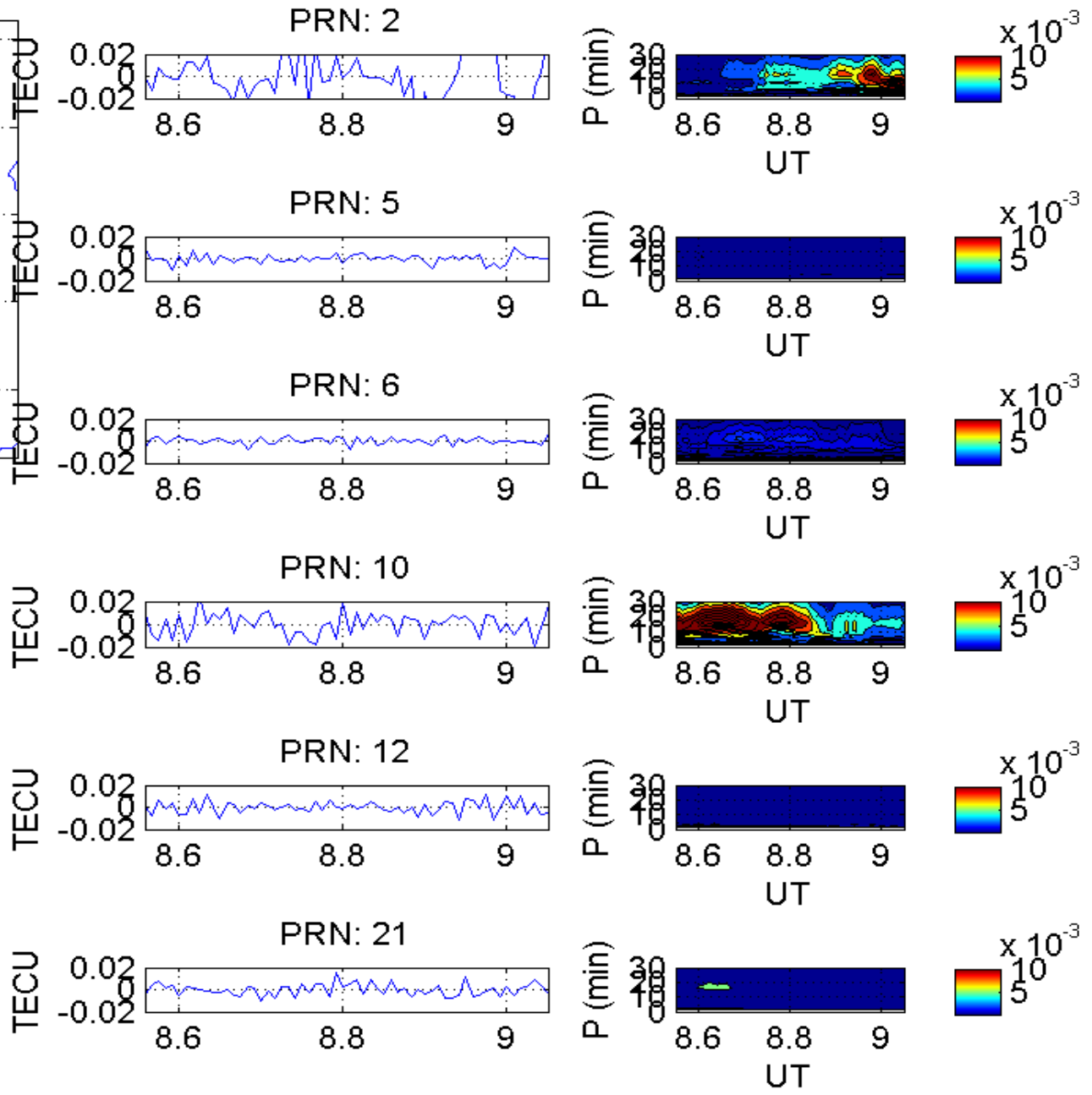


Results - Spectral Analysis - 6th Jan 2008

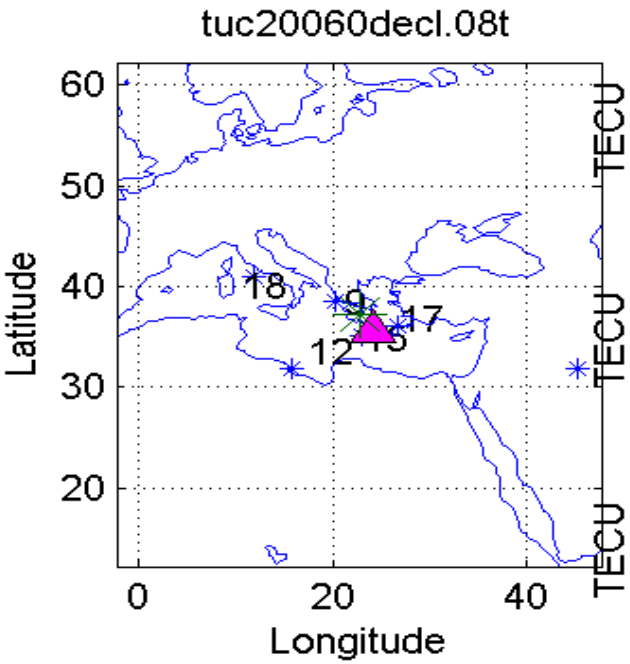


Mw = 6.2
R = 463 km
05:14 UT

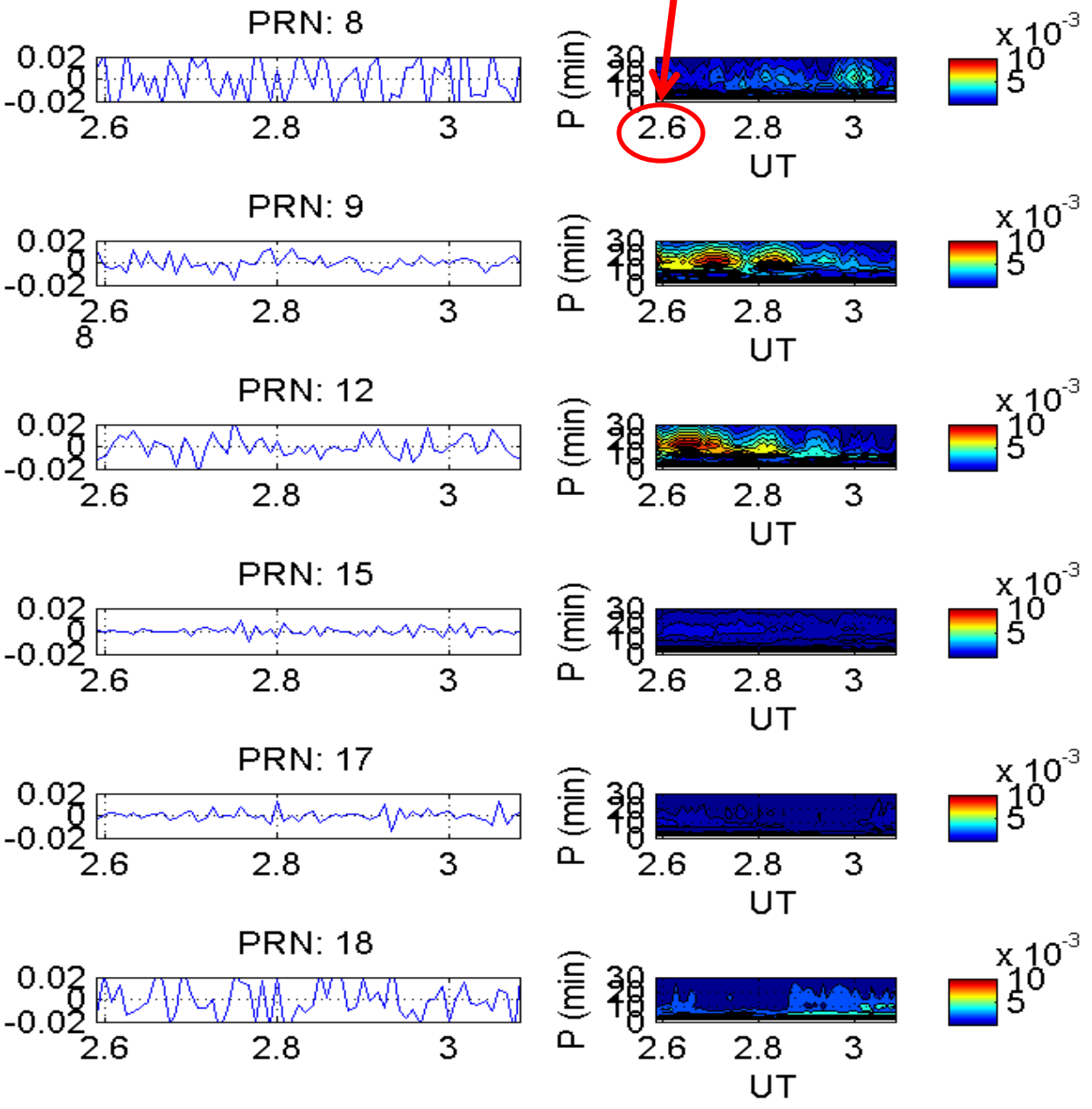
29th Dec 2007
Day of drop of R



Results - Spectral Analysis - 6th Jan 2008



≈3 hours before earthquake



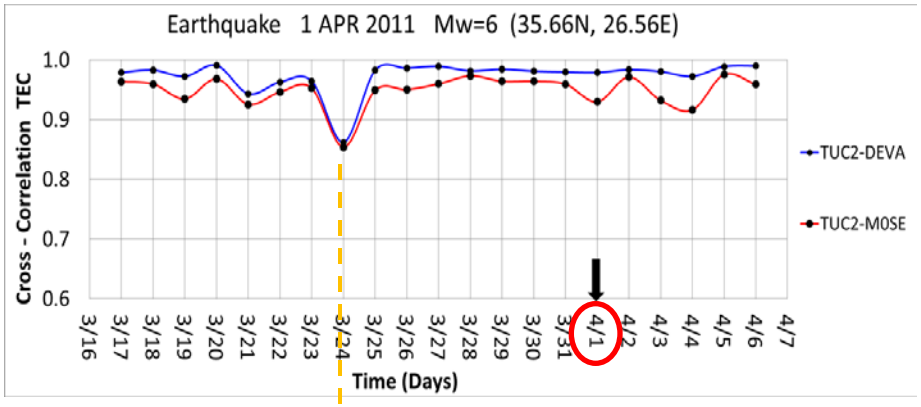
Mw = 6.2
R = 463 km
05:14 UT

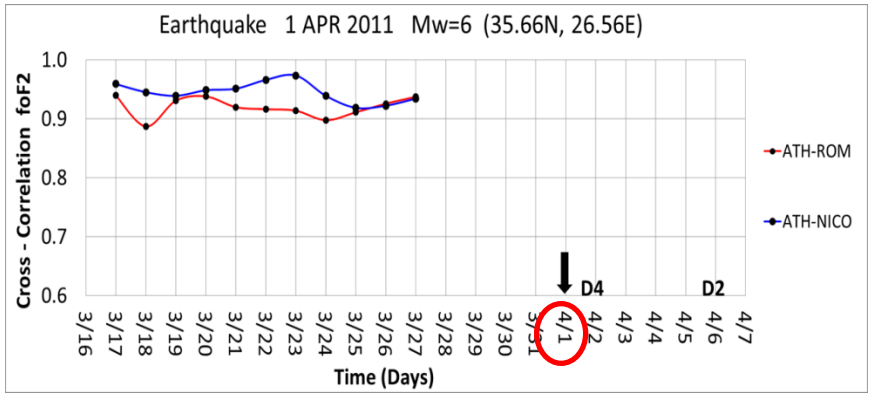
6th Jan 2008
Day of earthquake

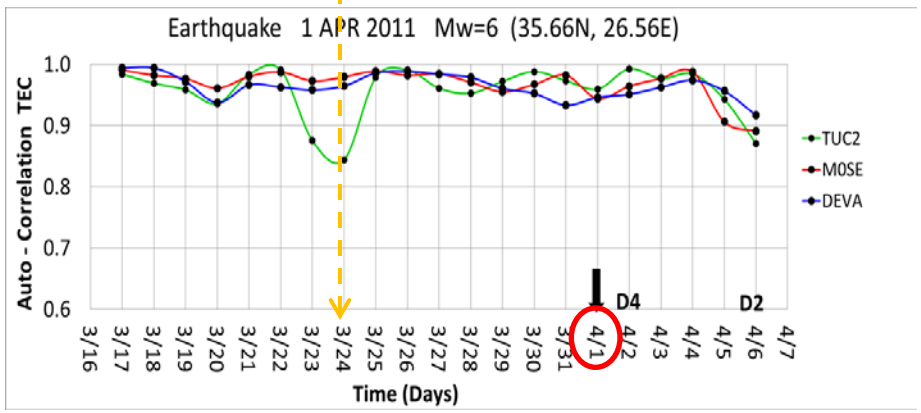
Results - Cross-correlation technique - 1st Apr 2011

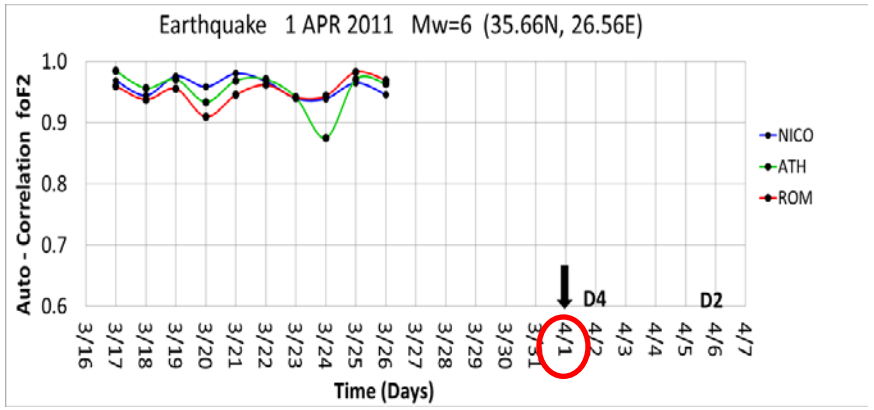
	1st Apr 2011	
Mw = 6	13:29 UT	R = 380 km

- **We can see a large drop of both auto (sensor st.) and cross correl coef 8 days before the earthquake. This is obvious both at TEC and foF2 plots.**

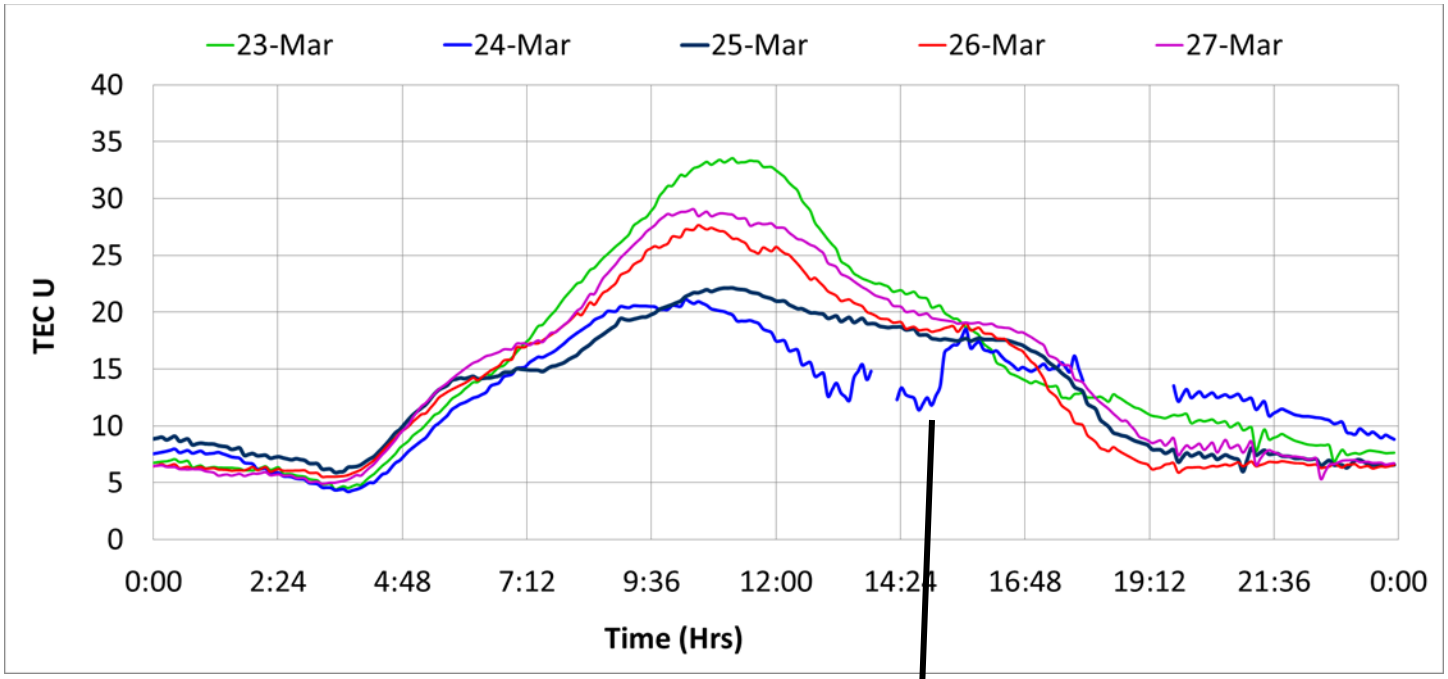






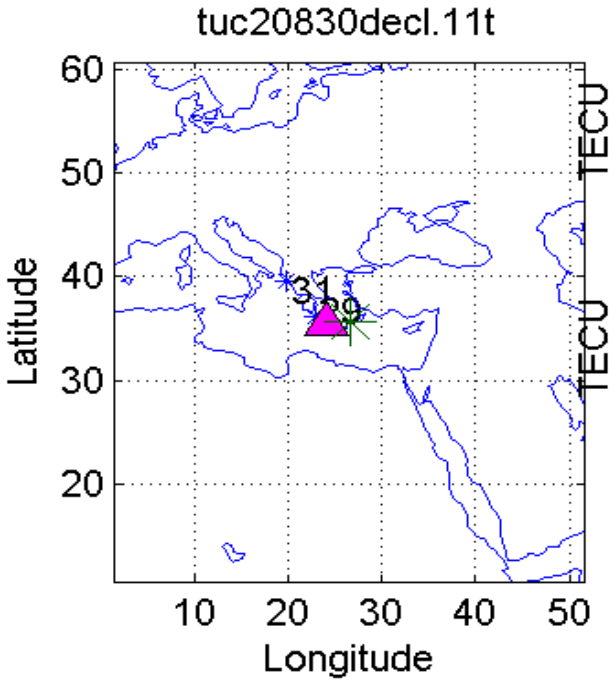


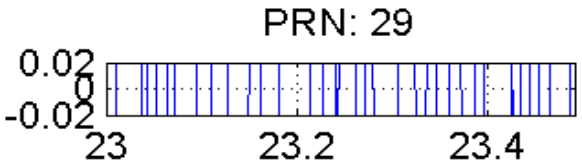
Results - 1st Apr 2011

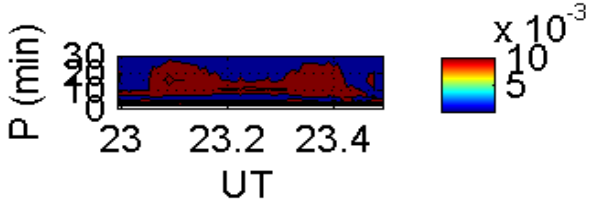


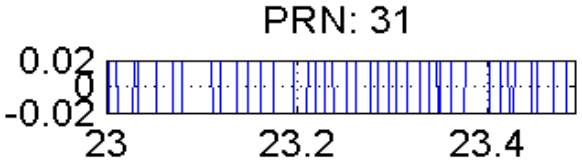
The TEC diurnal variation at 24th March where large drop of cross-correl coef was noted. There is a TEC drop which lasts for about 3hrs (11:00-14:30) unlike the other days.

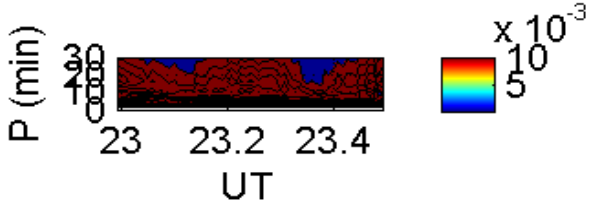
Results - Spectral Analysis - 1st Apr 2011











Mw = 6
R = 380 km
13:29 UT

24th March 2011
Day of drop of R

Conclusions

- The drop of the TEC cross-correlation coefficients coincides with the foF2 cross-correlation coefficients in all seismic events
- The cross-correlation coefficient appears to fall, in general, 12, 7, 5, 2 days before the earthquake or even at the day of earthquake as it had happened during the 6th of April 2009 earthquake at L' Aquila, Italy
- Spectral Analysis applied for maximum period of TEC oscillation up to 30 minutes is capable of distinguishing seismically induced TEC fluctuation anomalies from those generated by storms
- Since ionospheric perturbations induced by earthquakes are shadowed by ionospheric anomalies that are caused by geomagnetic storms, the simultaneous utilization of these techniques allow us to draw more safe conclusions in terms of identifying ionospheric precursors
- We have to calculate typical values of auto-correlation for quiet times in order to obtain indicative values under no earthquake or storm conditions to form a possible threshold measure.

Thank you!