# Ground based ULF and VLF seismo–electromagnetic investigations in Europe

**G. Prattes**[1], K. Schwingenschuh[1], H. U. Eichelberger[1], M. Y. Boudjada[1], B. F. Biagi[2], A. Rozhnoi[3], M. Solovieva[3], B. P. Besser[1], M. Stachel[1], I. Jernej[1], G. Berghofer[1], W. Magnes[1], D. Wolbang[4], P. Nenovski[5], U. Villante[6,7], M. Vellante[6,7]

[1] Space Research Institute, Austrian Academy of Sciences, Graz, Austria
[2] Department of Physics, University of Bari, Bari, Italy
[3] Institute of the Earth Physics, Russian Academy of Sciences, Moscow, Russia
[4] Institute of Physics, IGAM, KF University Graz, Graz, Austria
[5] Geophysical Institute, Sofia, Bulgaria
[6] Dipartimento di Fisica, Universit`a dell'Aquila, L'Aquila, Italy
[7] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

10.10. 2011 2nd INTERNATIONAL DEMETER WORKSHOP

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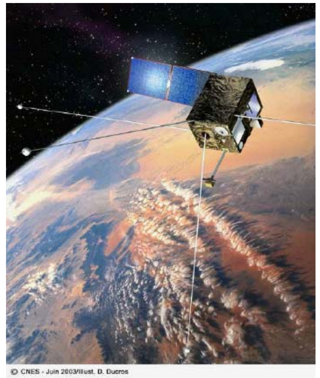
# Introduction

- During the **DEMETER** operational phase 2004-2010 we conducted complementary seismo-electromagnetic ground based ULF and VLF investigations.
- The 5 station South European Geomagnetic Array (**SEGMA**) provided ULF data with a nominal rate of 1 Hz, the European VLF receiver-transmitter network delivered 20 sec phase and amplitude values.
- The VLF radio links from the International Network for Frontier Research on Earthquake Precursors (**INFREP**) have been used as a tool to monitor seismic variations along the paths.
- Combined ULF and VLF studies was on the analysis of the **L'Aquila** 2009 earthquake (M=6.3). Several earthquake events, e.g. the earthquake in Serbia (**Kraljevo**) on Nov 3, 2010, (M=5.3) are investigated.
  - For ULF the improved polarization method was successfully applied in order to differentiate seismo-magnetic from geomagnetic variations in a time span of 1 year prior the L'Aquila earthquake.
  - In case of VLF the terminator time and monthly residual methods have been applied. Beside results from earthquakes, we are continuously investigating volcanic activities, e.g. Eyjafjallajökull and Grímsvötn, Island and Etna, Italy.
    - In terms of VLF, meteorological data (temperature, relative humidity, atmospheric pressure) are used to identify local disturbances.
    - Global geomagnetic indices (Dst, Kp) are environmental proxies.

# Instrumentation and data base




- The French satellite mission **DEMETER** (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions).
- GPS Total Electron Content (**TEC**) measurements.
- Complementary data is provided by the Graz seismo-electromagnetic VLF facility as part of a European ground based VLF receiver network (**INFREP**).
- Station network for combined investigations of geophysical/seismic phenomena, consisting of (i) VLF only (red markers), (ii) VLF/LF (green), (iii) South European Geomagnetic Array (**SEGMA**) ULF (blue) receiving stations, and (iv) European VLF transmitters (yellow), LF transmitters not shown (Schwingenschuh, et al. 2011).


- VLF receivers in the frequency range from 10 – 50kHz, operating with 20s resolution.

# Instrumentation and data base

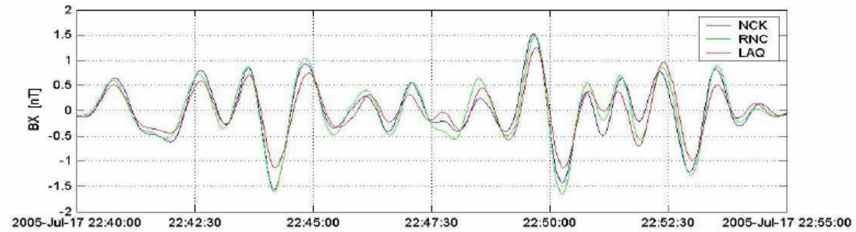
- South European Geomagnetic Array (SEGMA)
  - ULF fluxgate instruments providing magnetic field data recorded in mid- and south Europe

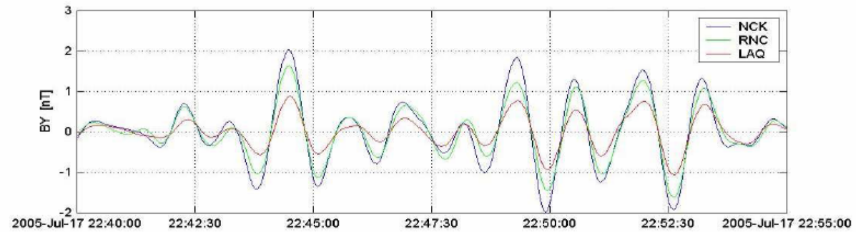
| ULF Stations | | Geographic Coordinates | | Corr. Geomagnetic Coordinates | | Dist |
|---|---|---|---|---|---|---|
| Name | Code | Lat.[° N] | Long.[° E] | Lat.[° N] | Long.[°E] | km |
| Castello Tesino | CST | 46.0 | 11.7 | 40.7 | 87.0 | 420 |
| Nagycenk | NCK | 47.6 | 16.7 | 42.6 | 91.7 | 630 |
| Ranchio | RNC | 43.97 | 12.08 | 38.22 | 86.71 | 200 |
| L'Aquila | AQU | 42.23 | 13.19 | 36.30 | 87.35 | 6 |
| Panagyurishte | PAG | 42.51 | 24.18 | 36.98 | 97.21 | 890 |


- The CHIMAG fluxgate magnetometer parameters

| | |
|---|---|
| Measurement range | +/- 512 nT |
| Compensation field | + 60000 nT in X and Z, +/- 30000 nT in Y |
| Accuracy | 8 pT |
| Sampling frequency | 64 Hz (highest possible) |
| Frequency resolution | 1 Hz |

- NCK, CST and RNC: CHIMAG FGM installed
- LAQ: FGM and search coil magnetometer
- PAG: Search coil magnetometer

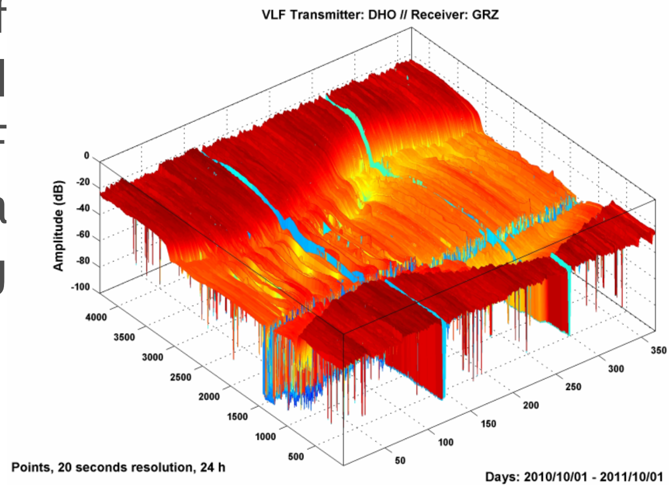


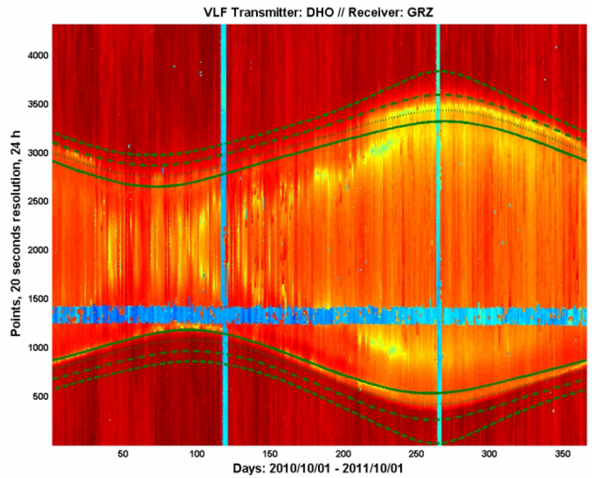



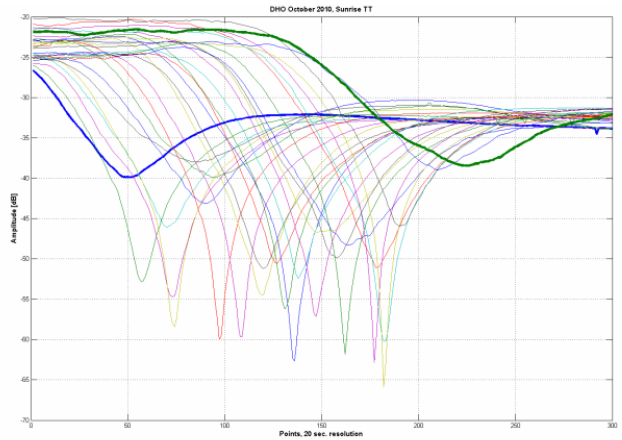

- Typical PC4 pulsations/17.7.2005 (22:40-22:55), period: 90s

# The VLF TT Method

- Terminator times are the positions of characteristic minima occurring in the diurnal dependencies of amplitude (and phase) of VLF/LF signals when the terminator crosses a propagation path during the evening and morning time periods
- E-W terminator time changes are expected
- Terminator minima are known to occur due to the interference between different waveguide modes



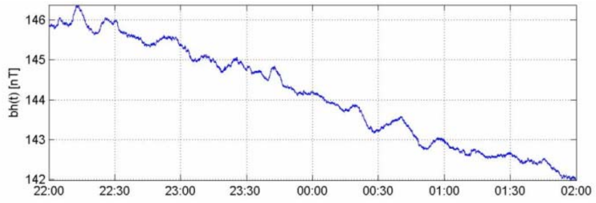



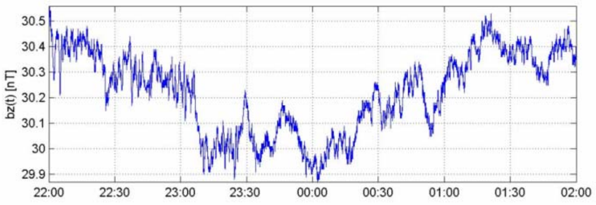




- Sunrise TT, DHO – GRZ from 1 – 31 Oct 2010. The average increase is ~2 minutes every day
- Sunrise / sunset from DHO – GRZ from 1 Oct 2010 – 1 Nov 2011 (official, civil, nautical, astronomical)

# Standardized ULF Polarization Method

1. Extract magnetic field data
   - Example for variations of $\delta b_h(t)$ and $\delta b_z(t)$ of four hours during the local midnight (22:00 – 02:00 LT)




2. Magnitude of FFT analysis performance
   - $|B_H(f)|$ and $|B_Z(f)|$
     - Sampling frequency fs = 1Hz -> Upper analyzable frequency $f_{NY}$= 0.5Hz
3. Estimation of the power spectral density $S_H$ and $S_Z$ in the sub-band 10 – 15mHz ($\Delta f_1$= 5mHz)
4. Standardized daily Horizontal (H) and Vertical (Z) intensity determination

$$H_{day} = \frac{S_{\Sigma \mathrm{Hday}} - \mu_{\Sigma \mathrm{Hmonth}}}{\sigma_{\Sigma \mathrm{Hmonth}}} \qquad Z_{day} = \frac{S_{\Sigma \mathrm{Zday}} - \mu_{\Sigma \mathrm{Zmonth}}}{\sigma_{\Sigma \mathrm{Zmonth}}}$$

5. Standardized Polarization (P) determination

$$P_{day} = \frac{Z_{day}}{H_{day}}$$

- Establishment of a robust threshold for the standardized daily $H_{day}$ intensity

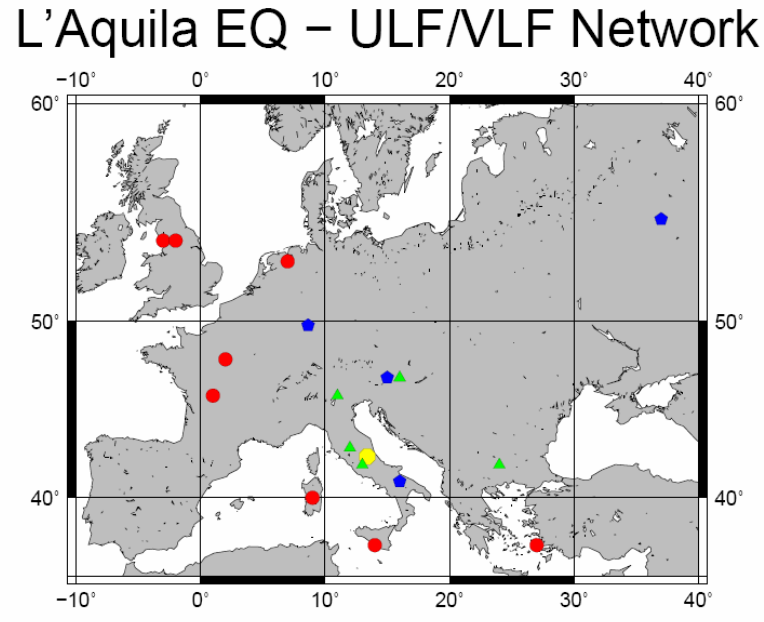
  If the $H_{day}$ decreases a high polarization value $P_{day}$ is resulted. Only if the standardized daily $H_{day}$ intensity is exceeding a certain value the polarization $P_{day}$ is considered

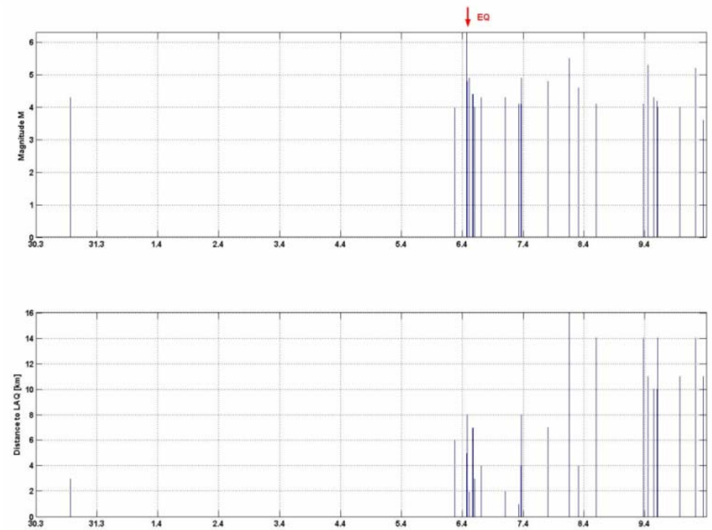
# The LAQ Earthquake

- On the example of the strong **L'Aquila earthquake** (Italy, M = 6.3, April 6, 2009) we refer to ground based **ULF** observations (Prattes et al., 2011).
  - Combine results to complementary **VLF** ground based measurements recorded in the local earthquake area.

- The VLF and ULF methods are complementary approaches.
  - Combined investigations improve the **characterization** of ionosphere perturbations.

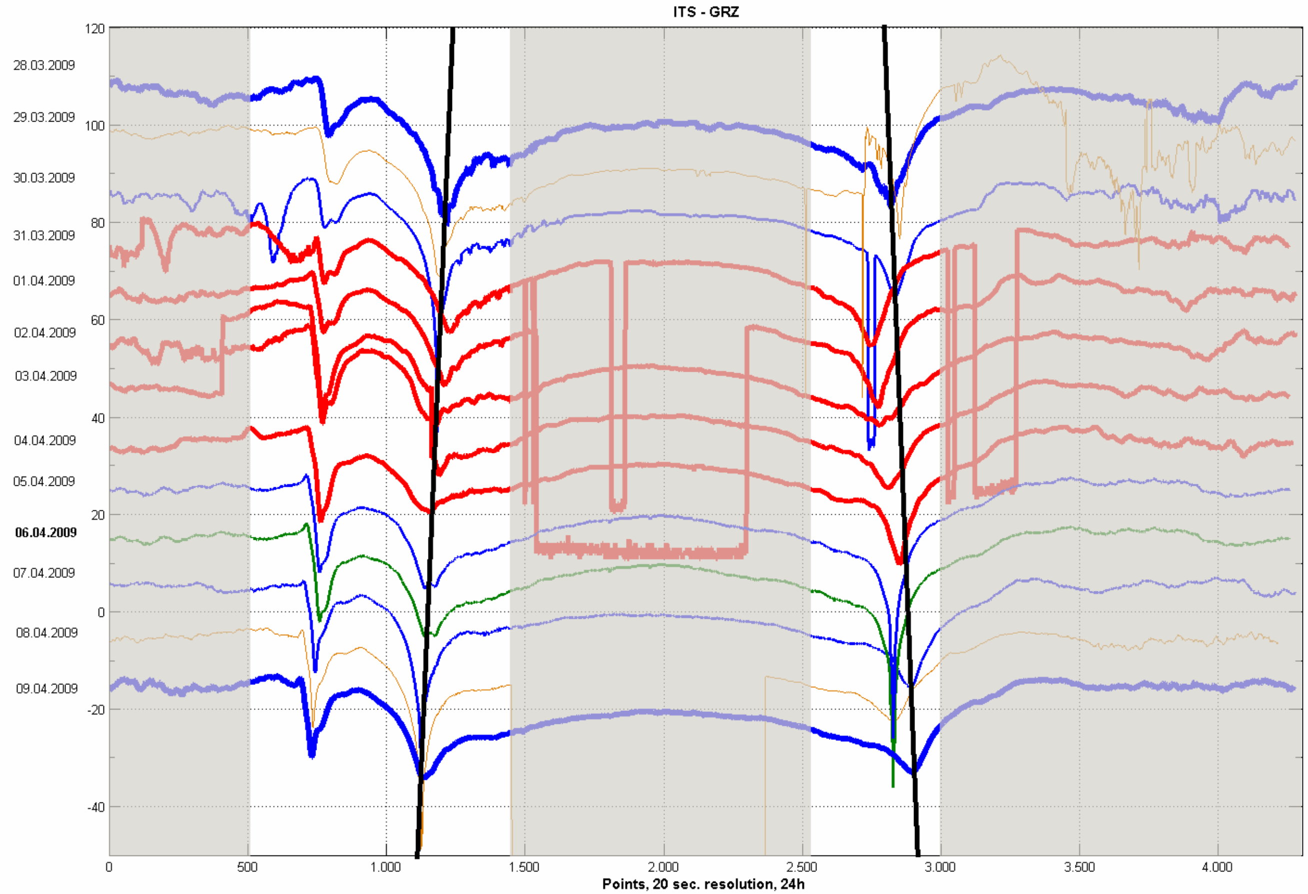
- We conclude that ground based services from ULF measurements can detect variations of atmospheric parameters on local and global scales.



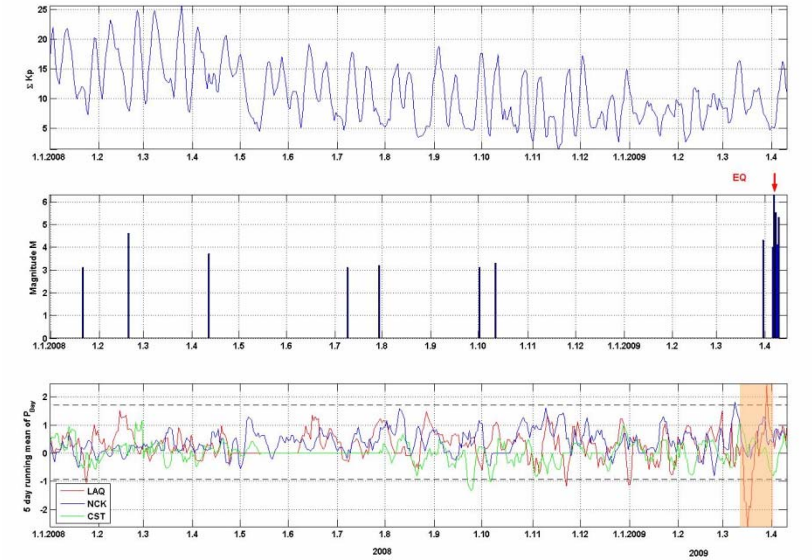

- LAQ Earthquake series with distance and magnitde from 30 Mar – 9 Apr 2009

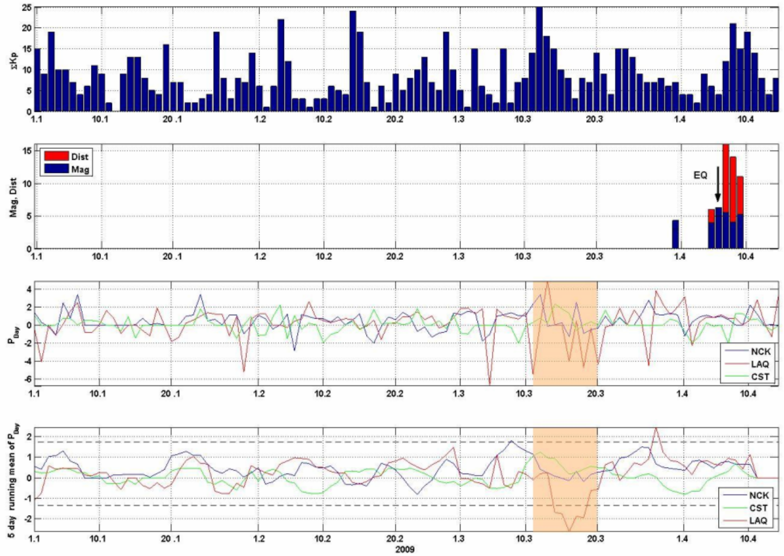
# The LAQ EQ VLF results

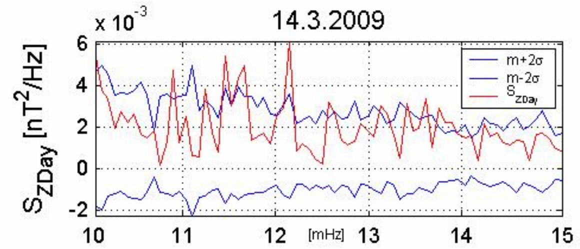


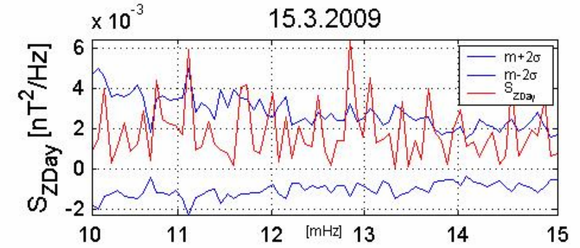

- Sequential plots of the diurnal variation in VLF signal amplitude along the path ITS – GRZ. The sunrise/sunset TT is where a minimum in amplitude takes place around sunrise and sunset, respectively. The data show an abnormal behavior in the diurnal variation beginning 7 days before the EQ from 31 March in the sunset TT. We have a shortening of daytime conditions to last for a few days before the EQ series main stroke (indicated green)

# The LAQ EQ ULF results



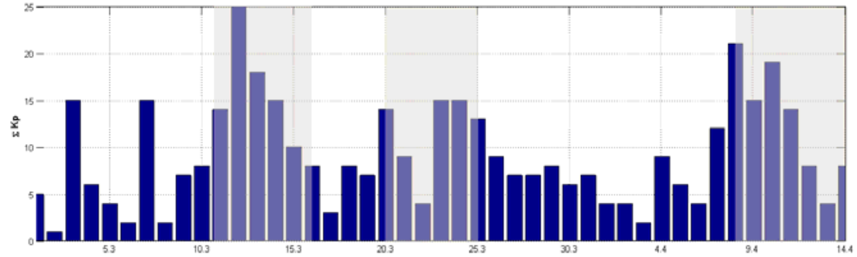



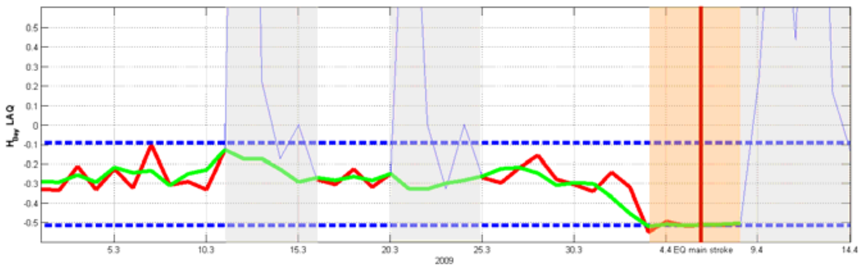



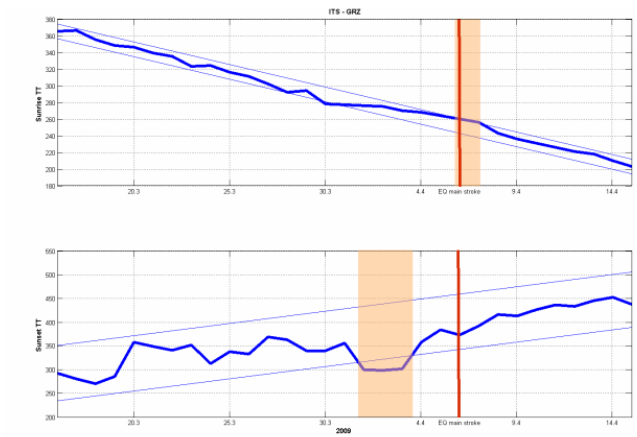




- Five day running mean of ΣKp, magnitude of the seismic events with the earthquake swarm in April 2009 and standardized polarization from 1 Jan – 14 Apr 2009 for CST, NCK and LAQ station (left)
- 5 day running mean, 10 March – 20 March 2009, LAQ standardized polarization → anomalies 2-3 weeks before the impending EQ series (right)
- Example of 2 disturbed days. The monthly vertical m±2σ is exceeded in the f-range from 10 – 15 mHz on March 14 and March 15 2009 (right bottom)

# ULF / VLF result comparison

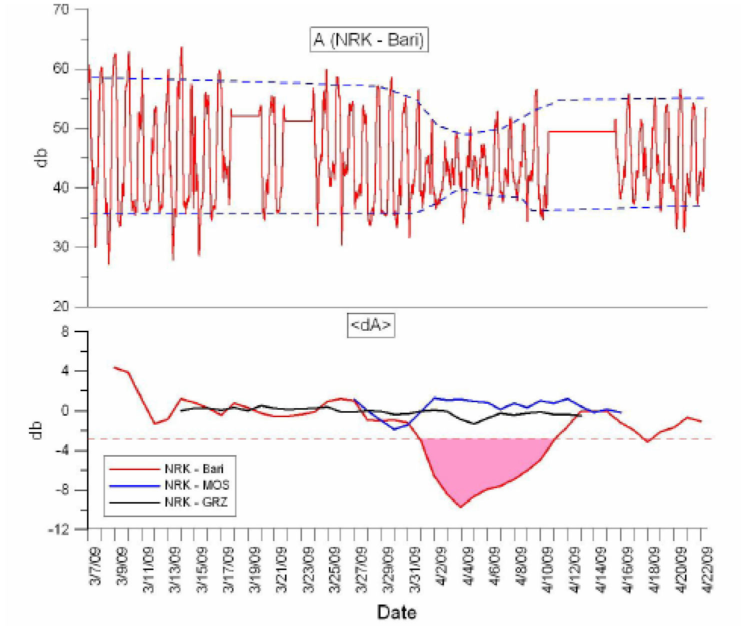



- Upper panel: Sunrise TT, Lower panel: Sunset TT on the path ITS – GRZ (compare Rozhnoi et al., 2009)

- Upper panel: KP index, lower panel: 5 day running mean of standardized H-magnetic field component from LAQ station (10 – 15mHz)



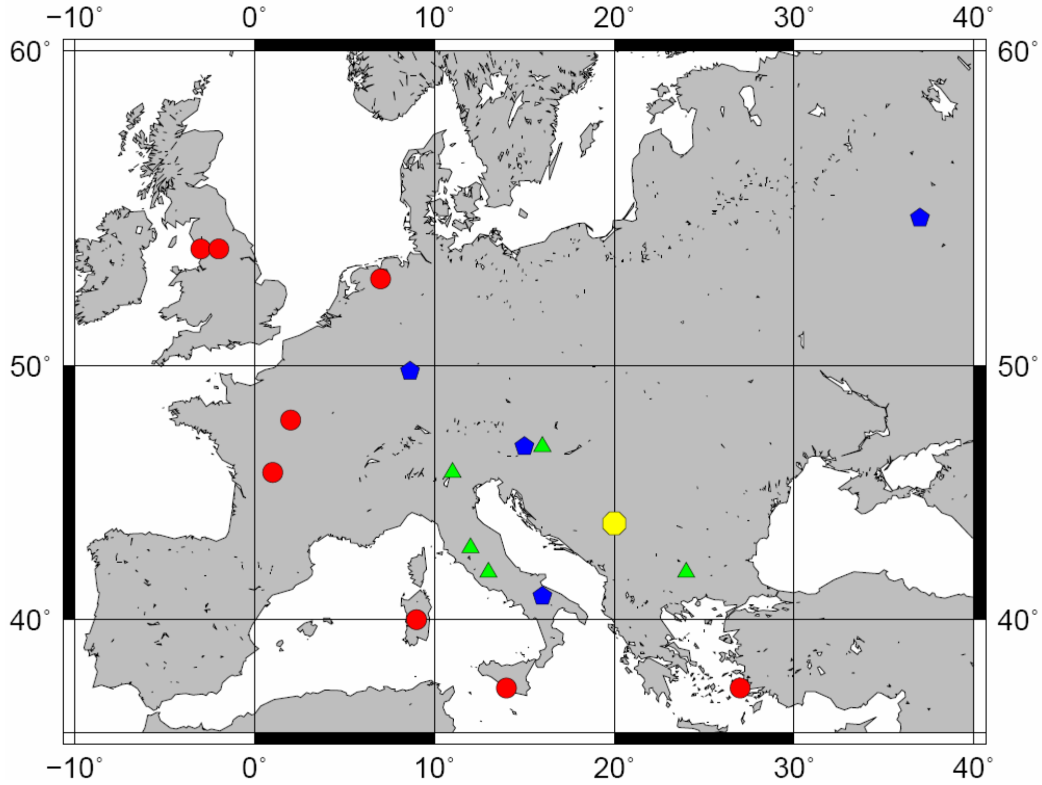

- Upper panel: signal amplitude (A) of the NRK signal recorded in Bari in the period 7 Mar – 22 Apr 2009. Lower panel: Nighttime residual amplitude (dA) for the path NRK-Bari, NRK-MOS and NRK – GRZ (Rozhnoi et al., 2009)

# The Kraljevo (Serbia) Earthquake

- The Kraljevo Earthquake
  - Date: 00:56:56 UTC, November 3, 2010
  - Magnitude: 5.3 $M_W$
  - Depth: 10km
  - Epicenter: 43.71°N, 20.62°E

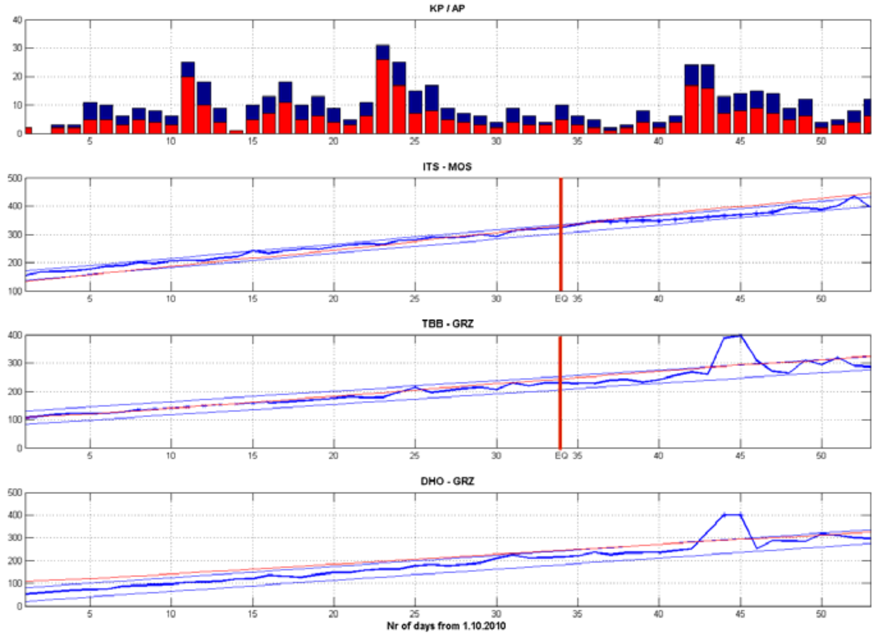
- The VLF paths ITS – MOS (d~ 2700 km) and TBB – GRZ (d~ 1300 km) cross the epicenter region. ICV – GRZ (d~820 km) and DHO – GRZ (d~860 km) are used as control paths

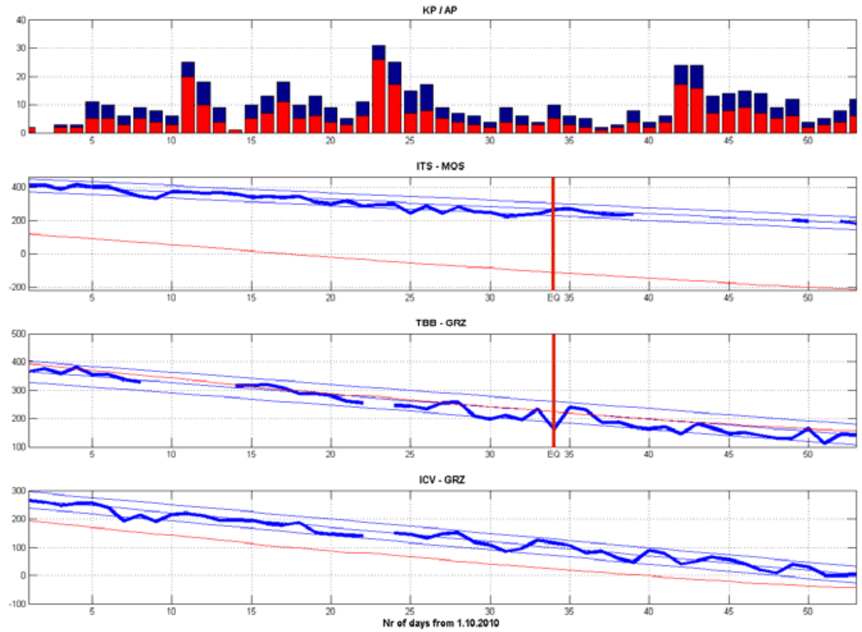
Serbia EQ – ULF/VLF Network




- VLF transmitter network (red), VLF receiver (blue diamonds), SEGMA ULF stations (green), the Kraljevo earthquake (yellow circle)

# The Kraljevo earthquake



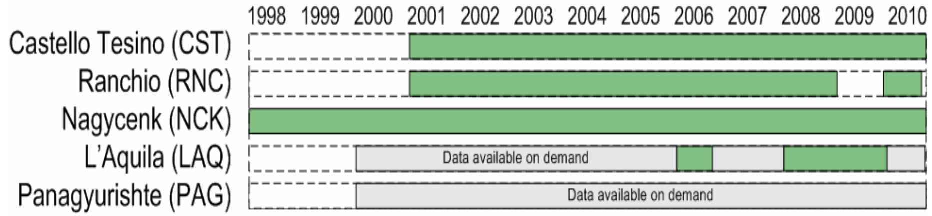




- KP/AP index
- Sunrise TT for paths ITS – MOS, TBB – GRZ, DHO – GRZ (control path) from 1 Oct 2010, theoretical TT in red
- Anomalies in the 13 Nov and 14, no clear anomalies related to the EQ

- KP/AP index
- Sunset TT for paths ITS – MOS, TBB – GRZ, ICV – GRZ (control path) from 1 Oct 2010, theoretical TT in red
- No clear anomalies related to the EQ, except a shift on 4 Nov on the path TBB–GRZ

# Data availability and DVT

- SEGMA and the VLF/LF network provide validated data with high reliability and continuously
- Software implementation for space science data visualisation **DVT** (Data Visualisation Tool)
- The data selection (mission, type, time, etc.) – top left
- Results of the database query – top right
- Visualization for required epoch, mission and possible dependability attributes – bottom left
- Templates for expanding to new ground or space based datasets – bottom right




- ULF data statistics from 1998 to 2010

# Conclusion and Outlook

- **Multi parameter**, e.g. combined satellite and ground based multi station seismo-electromagnetic studies lead to reliable results
- Both ULF and VLF pre-seismic anomalies are clearly correlated with the **L'Aquila earthquake** (for the remaining events the signal to noise ratios set the limit for analysis)
- The **Kraljevo (Serbia) earthquake** is on the lower magnitude level but two VLF paths pass the epicenter region. The preliminary results are inconclusive, further studies are necessary (missing phase analysis, residual method not yet applied and ULF complementary data are further analyzed)
- A **common data base** is necessary (contain combined electromagnetic ground based/satellite and seismic data)

Thanks