



BEYOND

Building a Centre of Excellence
for EO-based monitoring of Natural Disasters



Monitoring electromagnetic signals related to earthquakes with satellites and ground-based magnetometer arrays

Georgios Balasis

National Observatory of Athens

Outline

- The ENIGMA magnetometer array within the frame of BEYOND Center of Excellence
- Electromagnetic (EM) signals related to earthquakes (EQs)
 - Ground-based studies
 - Satellite studies

HellENIC GeoMagnetic Array (ENIGMA)

- The National Observatory of Athens (NOA) currently operates ENIGMA (HellENic GeoMagnetic Array), an array of 3 ground-based magnetometer stations in the areas of Trikala (Klokotos), Attiki (Dionysos) and Lakonia (Velies).
- ENIGMA provides measurements for the study of geomagnetic pulsations, resulting from the solar wind-magnetosphere coupling.
- Ground-based magnetometers have proven to be the workhorse of magnetosphere-ionosphere coupling physics.

BEYOND & ENIGMA

- Ground magnetometers enable effective remote sensing of geospace dynamics and therefore their importance in space weather monitoring and research is indisputable.
- ***The ENIGMA network is used within BEYOND in an attempt to address the issue of earthquake predictability by studying electromagnetic signals attributed to the coupled lithosphere-atmosphere-ionosphere system as one of the most promising potential pre-seismic transients.***

The old ENIGMA website

Institute for Astronomy, As... x ENIGMA x +

proteus.space.noa.gr/~srtg/index.php/groupfacilities/2-uncategorised/20-geomag

Search

Space Research & Technology Group

Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing

National Observatory of Athens

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ENIGMA

The Space Research and Technology Group operates the Hellenic GeoMagnetic Array (ENIGMA), an array of 3 ground-based magnetometer stations in the areas of Trikala (Klokotos), Attiki (Dionysos) and Lakonia (Velies) that provides measurements for the study of geomagnetic pulsations, resulting from the solar wind - magnetosphere coupling. ENIGMA is the first magnetometer station array that has ever operated in Greece and within a few years of operation has achieved to become a SuperMAG contributor.

SuperMAG is a worldwide collaboration of organizations and national agencies that currently operate more than 300 ground-based magnetometers. SuperMAG provides easy access to validated ground magnetic field perturbations in the same coordinate system, identical time resolution and with a common baseline removal approach. The purpose of SuperMAG it to help scientists, teachers, students and the general public have easy access to measurements of the Earth's magnetic field.

Ground-based magnetometers have proven to be the workhorse of magnetosphere-ionosphere coupling physics. Ground magnetometers enable effective remote sensing of geospace dynamics and therefore their importance in space weather monitoring and research is indisputable.

The Earth's Magnetic Field

IAASARS

ΕΠΙΣΤΗΜΟΝ ΑΝΤΙΦΟΡΕΚΟΜΗΤΩΝ ΑΘΗΝΩΝ

10:08 πμ 14/10/2015

The new ENIGMA website: www.enigma.space.noa.gr

Hellenic GeoMagnetic Array (E... x

enigma.space.noa.gr

dst kyoto wdc

IAASARS

Hellenic
GeoMagnetic Array
ENIGMA

Space Research & Technology Group

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ENIGMA STATIONS

ENIGMA DATA AND PRODUCTS

OUR TEAM

THE EARTH'S MAGNETIC FIELD

READ MORE

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WELCOME TO ENIGMA

The Space Research and Technology Group operates the Hellenic GeoMagnetic Array (ENIGMA), an array of 3 ground-based magnetometer stations in the areas of Trikala (Klokotos), Attiki (Dionysos) and Lakonia (Velies) that provides measurements for the study of geomagnetic pulsations, resulting from the solar wind - magnetosphere coupling.

ABOUT US

2:16 PM
16/5/2016

A new geophysical service offered by BEYOND

Hellenic GeoMagnetic Array (E... x

enigma.space.noa.gr

dst kyoto wdc

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Ελλάδα

ΚΛΟΚΟΤΟΣ (ΤΡΙΚΑΛΑ) Magnetome...

Αθηνών (ΔΙΟΝΥΣΟΣ (ΔΙΟΝ)) Magnet...

ΒΕΛΙΕΣ (ΛΑΚΩΝΙΑ) Magnetome...

READ MORE

WELCOME TO ENIGMA

The Space Research and Technology Group operates the Hellenic GeoMagnetic Array (ENIGMA), an array of 3 ground-based magnetometer stations in the areas of Trikala (Klokotos), Attiki (Dionysos) and Lakonia (Velies) that provides measurements for the study of geomagnetic pulsations, resulting from the solar wind - magnetosphere coupling.

ABOUT US

Windows taskbar: Total Commande..., Skype, MATLAB R2012b, Editor - C:\lib\W..., SwarmGui_unifie..., Signal Plotter v1.5..., BEYOND_ENIGMA, 2:17 μμ, 16/5/2016

A new geophysical service offered by BEYOND

enigma.space.noa.gr

dst kyoto wdc

STATION LOCATIONS

Click [here](#) to see the ENIGMA geomagnetic observatories.

STATION	STATION CODE	LOCATION	LATITUDE	LONGITUDE	ALTITUDE
KLOKOTOS (THL)	THL	Klokotos	39.5646°N	22.0144°E	86 m
DIONYSOS (DION)	DION	Dionysos	38.0779°N	23.9331°E	460 m
VELIES (VLI)	VLI	Velies	36.7180°N	22.9468°E	220 m

ENIGMA INSTRUMENTATION

- THL: GEOMAG-02 magnetotelluric station (GEOMAGNET, Ukraine)
- DION: GEOMAG-02M fluxgate magnetometer (GEOMAGNET, Ukraine)
- VLI: GEOMAG-02 magnetotelluric station (GEOMAGNET, Ukraine)
- didD Magnetic Observatory System SB2 with GSM-90F5D (GEM Systems, Canada)
- GSM-90F1 v7.0 Overhauser magnetometer (GEM Systems, Canada)
- 2 x Observatory variometer CTU-Vario (Czech Technical University in Prague)
- D/I theodolite THEO 010 (MinGeo, Hungary)
- GEOMAG-02 sensor (GEOMAGNET, Ukraine)
- Ag/AgCl electrodes (GFZ Potsdam, Germany)

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GEOMAG-02 instrument

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The screenshot shows a web browser window displaying the ENIGMA website. The browser tabs include 'SuperSpeed > status', 'SquirrelMail 1.4.22', 'Institute for Astronomy, Astrophys...', and 'Hellenic GeoMagnetic Array (ENIGMA)'. The address bar shows 'enigma.space.noa.gr'. The website has a blue header with the IAASARS logo and the text 'Hellenic GeoMagnetic Array ENIGMA Space Research & Technology Group'. A left sidebar contains navigation links: HOME, ABOUT US, SCIENTIFIC INFO, ENIGMA STATIONS, ENIGMA DATA AND PRODUCTS (highlighted), and OUR TEAM. The main content area features a green header 'ENIGMA DATA AND PRODUCTS'. Below it is a section titled 'DATA COVERAGE?' with a horizontal bar chart showing data availability for three stations: DION (yellow), THL (red), and VLI (blue) from 2008 to 2017. The chart shows DION starting in 2012, THL from 2008 to 2010 and 2015 to 2016, and VLI from 2008 to 2011 and 2012 to 2015. Below the chart are navigation icons and a 'Reset' button. The 'MAGNETOGRAMS' section contains a form with the following fields:

Date ?		Station	Plot type	Variables ?
From:	2008 / Jan / 01 00 : 00 Calendar	DION <input type="checkbox"/> VLI <input type="checkbox"/> THL <input type="checkbox"/>	One var per graph	ΔB_x <input type="checkbox"/> ΔB_y <input type="checkbox"/> ΔB_z <input type="checkbox"/>
To:	2008 / Jan / 01 00 : 00 Calendar		One station per graph	

Below the form are 'Search' and 'Last Daily Plot' buttons. The Windows taskbar at the bottom shows the system clock as 11:06 πμ 17/5/2016.

A new geophysical service offered by BEYOND

The screenshot shows a web browser window with the URL `enigma.space.noa.gr`. The page features a blue sidebar on the left with the IAASARS logo and the text "Hellenic GeoMagnetic Array ENIGMA Space Research & Technology Group". The sidebar contains navigation links: HOME, ABOUT US, SCIENTIFIC INFO, ENIGMA STATIONS, ENIGMA DATA AND PRODUCTS, and OUR TEAM.

The main content area is titled "MAGNETOGRAMS" and contains a search form with the following fields:

	Date ?	Station	Plot type	Variables ?
From:	2008 / Jan / 01 00 : 00 Calendar			
To:	2008 / Jan / 01 00 : 00 Calendar	<input type="checkbox"/> DION <input type="checkbox"/> VLI <input type="checkbox"/> THL	One var per graph One station per graph	<input type="checkbox"/> ΔBx <input type="checkbox"/> ΔBy <input type="checkbox"/> ΔBz

Buttons: Search, Last Daily Plot

Text: For ENIGMA data request please contact with Dr. G. Balasis.

The second section is titled "DAILY WAVELET SPECTRA" and contains a search form with the following fields:

Date	Station	Bandwidth
2008 / Jan / 01 Calendar	DION	Pc3

Buttons: Search, Last One Available

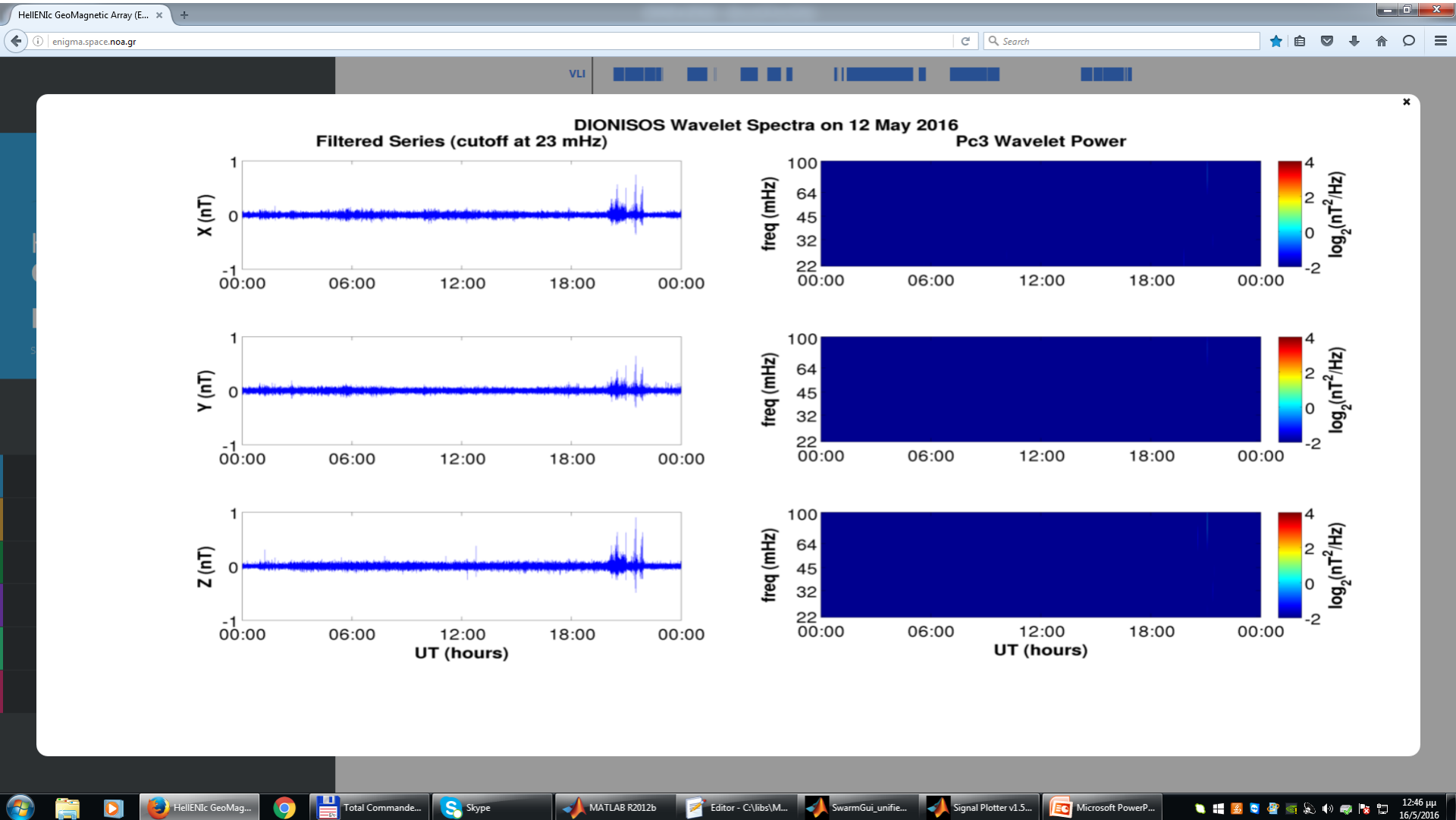
Text: For ENIGMA data request please contact with Dr. G. Balasis.

The Windows taskbar at the bottom shows the system clock as 11:07 πμ 17/5/2016.

Geomagnetic data service offered by BEYOND

The screenshot shows a web browser window displaying the ENIGMA data service interface. The browser address bar shows 'enigma.space.noa.gr'. The website header includes the IAASARS logo and the text 'Hellenic GeoMagnetic Array ENIGMA Space Research & Technology Group'. A navigation menu on the left lists 'HOME', 'ABOUT US', 'SCIENTIFIC INFO', 'ENIGMA STATIONS', 'ENIGMA DATA AND PRODUCTS', and 'OUR TEAM'. The main content area features a green button labeled 'ENIGMA DATA AND PRODUCTS'. A modal window titled 'Magnetogram(s) for 2016-05-12 00:00:00 - 2016-05-12 23:59:59' is open, showing a plot for station 'DION'. The plot displays three time-series data series: ΔB_x (black line), ΔB_y (blue line), and ΔB_z (red line), measured in nT. The x-axis represents time from 00:00:00 to 21:00:00, and the y-axis represents the magnetic field variation in nT, ranging from 10 to 65. A legend in the bottom right of the plot area identifies the lines: ΔB_x (black dot), ΔB_y (blue dot), and ΔB_z (red dot). Below the plot, there is a 'Variables?' section with checkboxes for ΔB_x , ΔB_y , and ΔB_z , all of which are checked. An 'OK' button is located at the bottom right of the modal window. Below the plot, a note reads: 'For ENIGMA data request please contact with Dr. G. Balasis.' The bottom of the screenshot shows a Windows taskbar with various application icons and a system clock showing 12:42 PM on 16/5/2016.

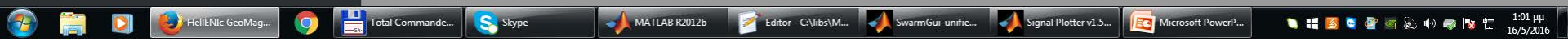
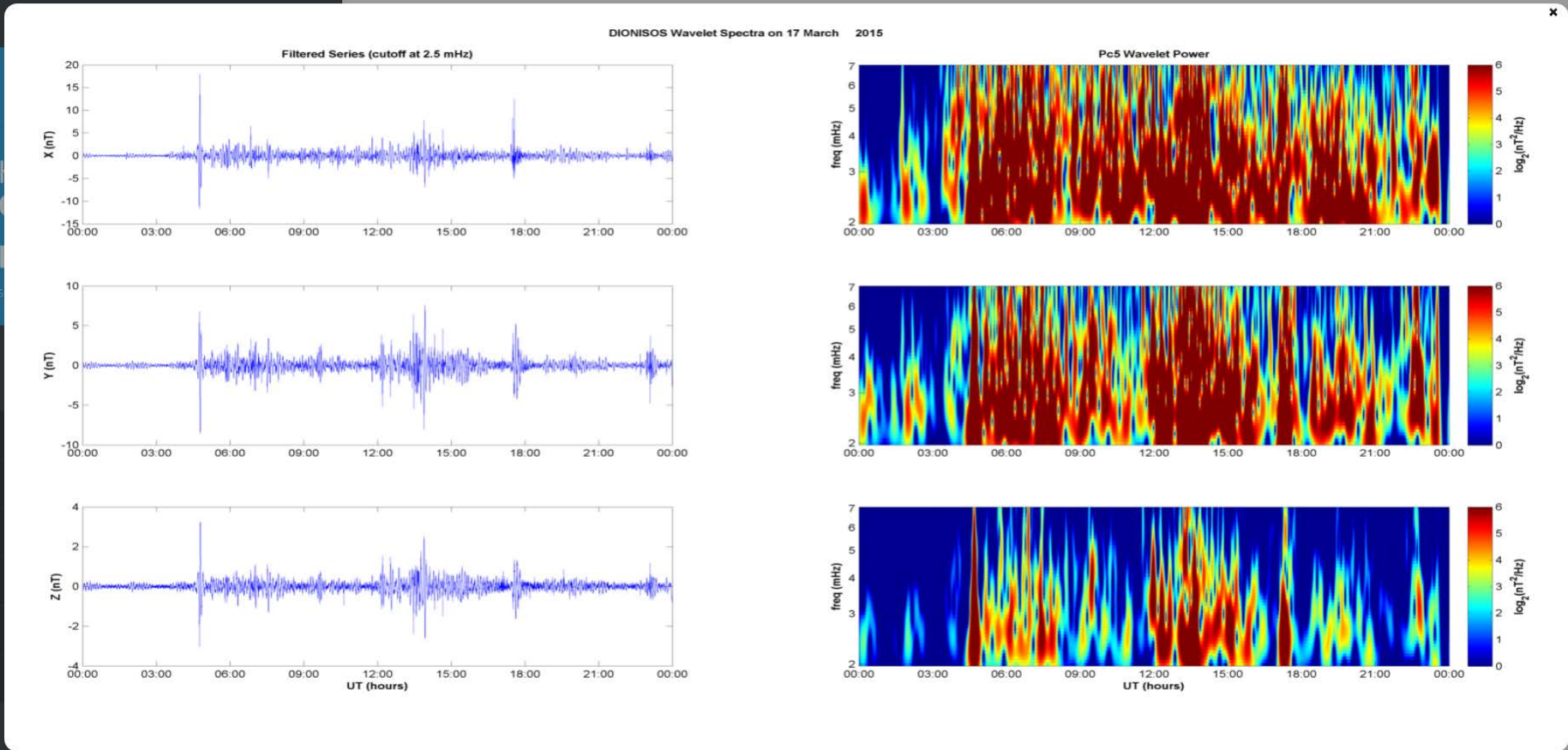
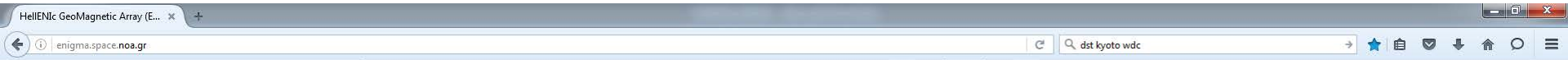
Geomagnetic data service offered by BEYOND



Geomagnetic data service offered by BEYOND

The screenshot displays the ENIGMA data service interface. On the left is a navigation menu with the following items: HOME, ABOUT US, SCIENTIFIC INFO, ENIGMA STATIONS, ENIGMA DATA AND PRODUCTS (highlighted in green), and OUR TEAM. The main content area features a green header 'ENIGMA DATA AND PRODUCTS' and a central plot window titled 'Magnetogram(s) for 2015-03-16 00:00:00 - 2015-03-18 23:59:00' for station 'DION'. The plot shows three time-series data series: ΔB_x (black), ΔB_y (blue), and ΔB_z (red) in nT. The y-axis ranges from -250 to 50 nT, and the x-axis shows time from 03/16 00:00 to 03/18 12:00. A legend in the bottom right of the plot window identifies the series: ΔB_x (black dot), ΔB_y (blue dot), and ΔB_z (red dot). Below the legend is an 'OK' button. To the right of the plot, a 'Variables?' section shows checkboxes for ΔB_x , ΔB_y , and ΔB_z , all of which are checked. The browser's address bar shows 'enigma.space.noa.gr' and the search bar contains 'dst kyoto wdc'. The Windows taskbar at the bottom shows various open applications including MATLAB R2012b, Editor, SwarmGui, Signal Plotter, and Microsoft PowerPoint, along with the system clock showing 12:56 PM on 16/5/2016.

Geomagnetic data service offered by BEYOND



EM signals related to EQs: Proof of concept

bbnet.gein.noa.gr/HL/database

Database of revised events

Date	Latitude	Longitude	Depth (km)	Local magnitude
FROM: 2011 / Jan / 01	33.5110	18.8439	0	5
TO: 2016 / Apr / 30	42.4428	29.4344	20	8

Search

Χάρτης Δορυφόρος

INSTITUTE OF GEODYNAMICS
NATIONAL OBSERVATORY OF ATHENS

Local Magnitude	Depth (Km)
M <= 2.5	< 15
2.5 < M <= 4.0	15 - 30
4.0 < M <= 5.0	30 - 60
M >= 5.0	60 - 100
	>= 100

Manual alerts

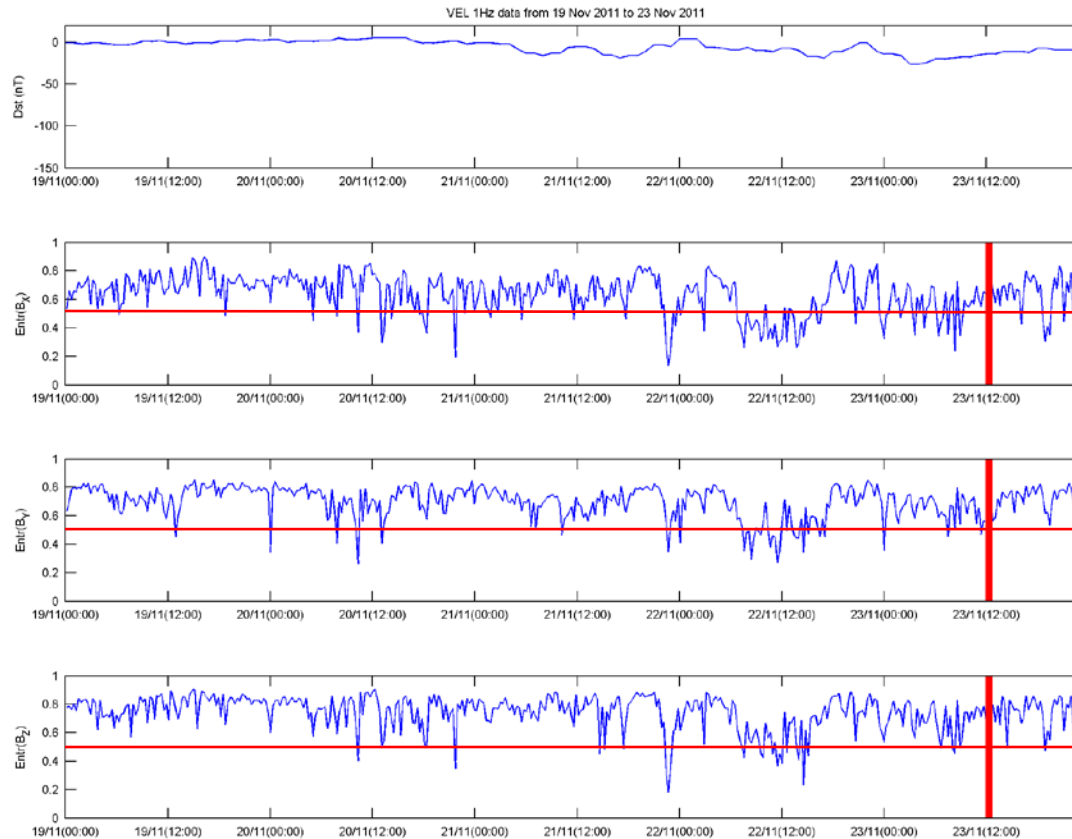
Origin Time	Magnitude
29/03/2016 01:05:28	ML: 5.2, Mw: 5.2
17/11/2015 08:33:40	ML: 5.1, Mw: 5.0
17/11/2015 07:10:07	ML: 6.0, Mw: 6.4
09/06/2015 21:49:46	ML: 5.4, Mw: 5.4
09/06/2015 01:09:03	ML: 5.3, Mw: 5.2
08/11/2014 23:15:42	ML: 5.0, Mw: 5.0
24/10/2014 23:43:15	ML: 5.2, Mw: 5.1
03/02/2014 03:08:44	ML: 5.7, Mw: 5.9
26/01/2014 18:45:08	ML: 5.1, Mw: 5.3
26/01/2014 13:55:43	ML: 5.8, Mw: 6.0
07/08/2013 09:06:51	ML: 5.2, Mw: 5.4
17/02/2013 03:12:52	ML: 5.0, Mw: 4.9
23/11/2011 12:17:48	ML: 5.1, Mw: 5.3
19/07/2011 07:13:12	ML: 5.0, Mw: 4.9

Origin Time

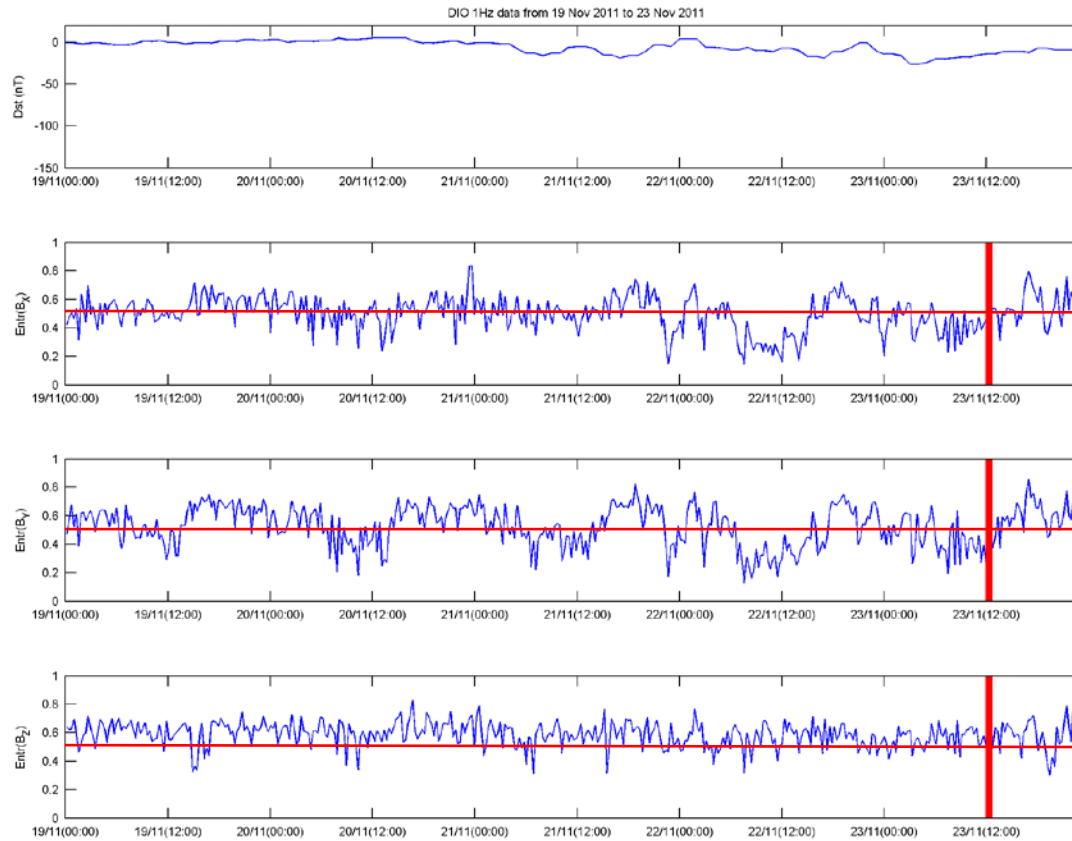
BBNET - Database... Total Commande... Skype BEYOND_ENIGMA

5:09 μμ 16/5/2016

Entropy analysis of Velies data around 23/11/2011 M5 EQ



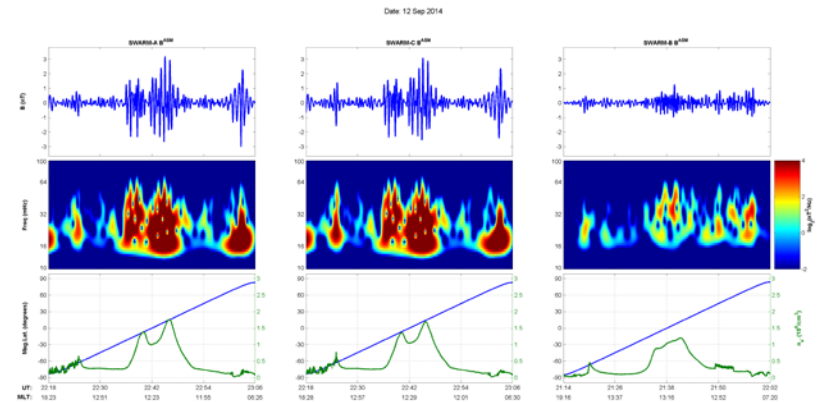
Entropy analysis of Dionysos data around 23/11/2011 M5 EQ



ULF wave power features in the topside ionosphere revealed by Swarm observations

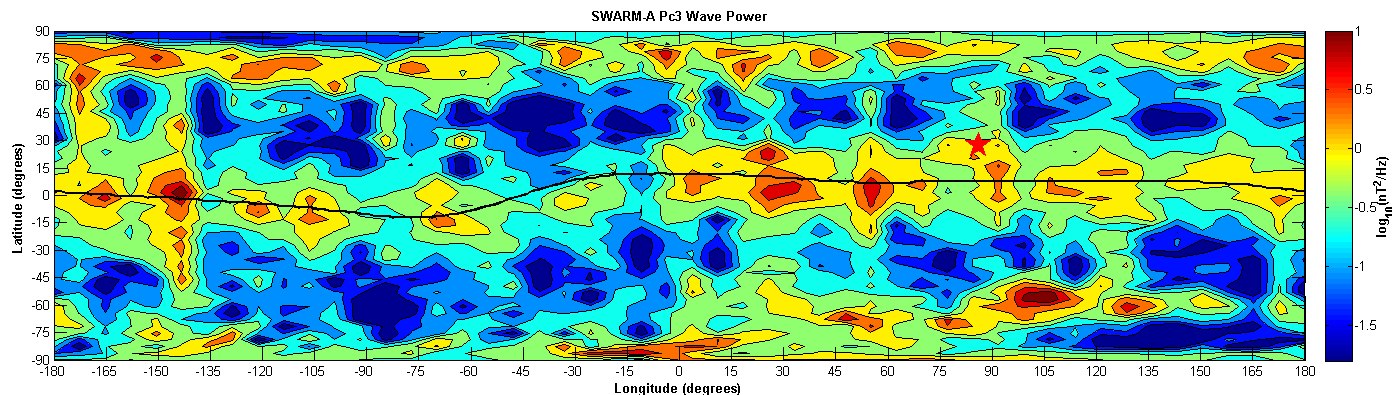
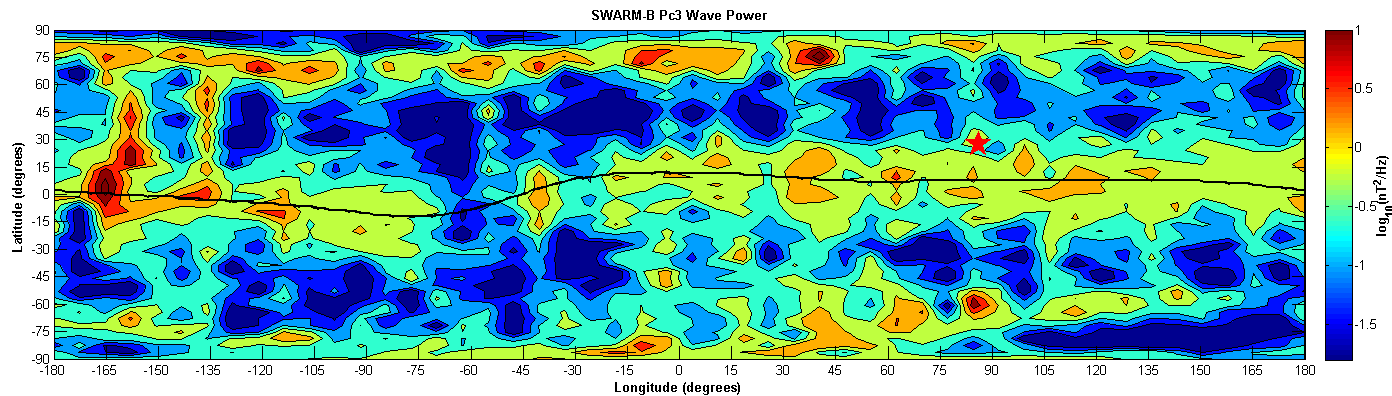


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- Balasis, G., C. Papadimitriou, I. A. Daglis, and V. Pilipenko (2015), *Geophys. Res. Lett.*, 42, 6922–6930, doi:10.1002/2015GL065424.

Swarm Pc3: Apr 1st – June 15th 2014



“Swarm & Nepal EQ (25/4/2015)”

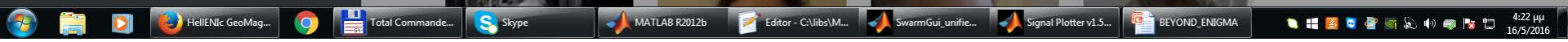
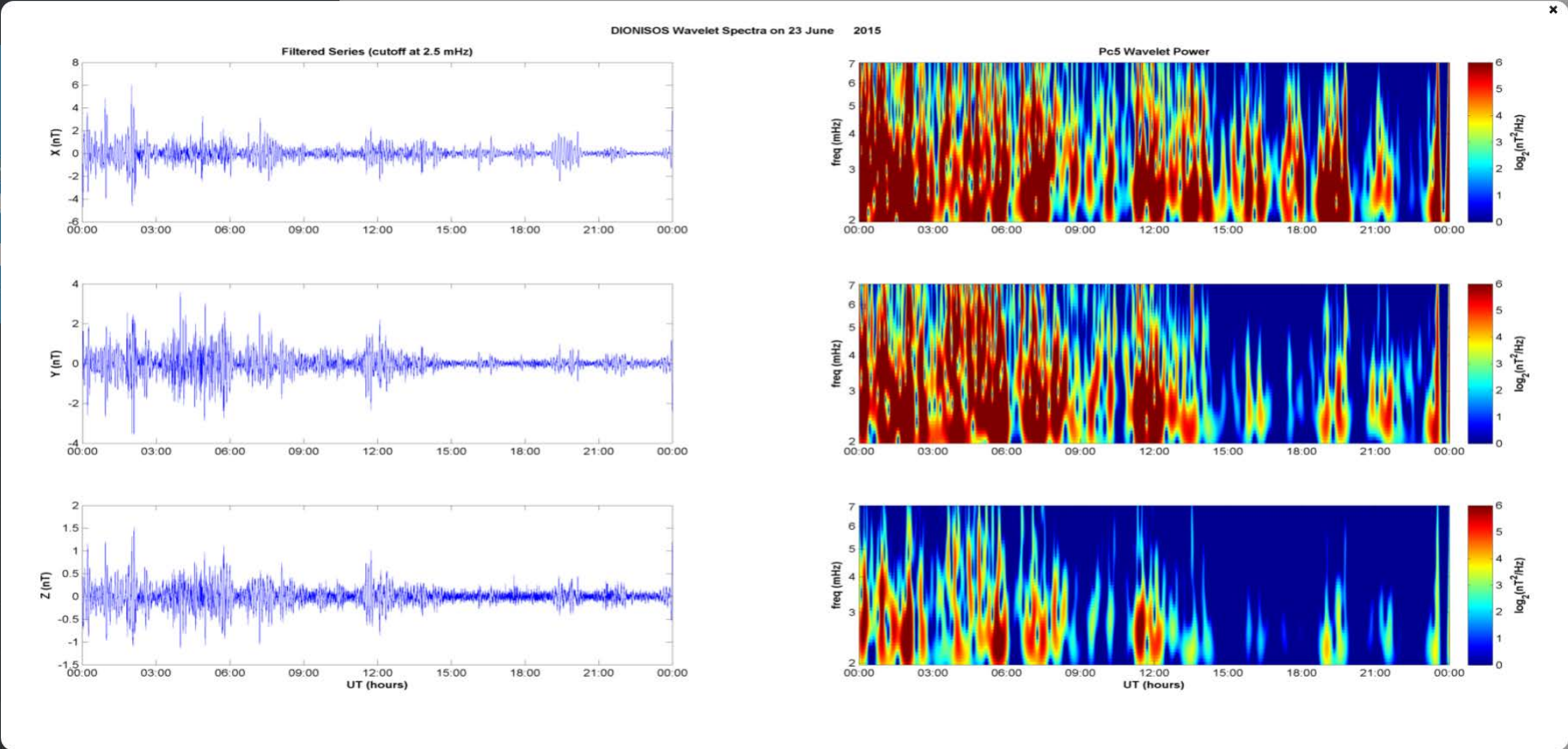
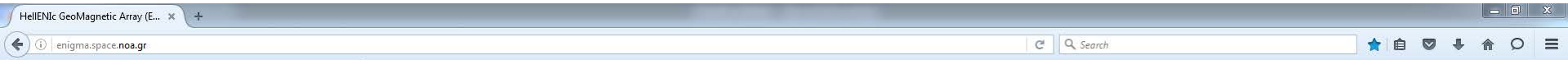
Geomagnetic data service offered by BEYOND

The screenshot displays the ENIGMA website interface. On the left is a navigation menu with the following items: HOME, ABOUT US, SCIENTIFIC INFO, ENIGMA STATIONS, ENIGMA DATA AND PRODUCTS (highlighted in green), and OUR TEAM. The main content area features a green header for "ENIGMA DATA AND PRODUCTS" and a central plot window titled "Magnetogram(s) for 2015-06-22 00:00:00 - 2015-06-24 23:59:00" for station "DION".

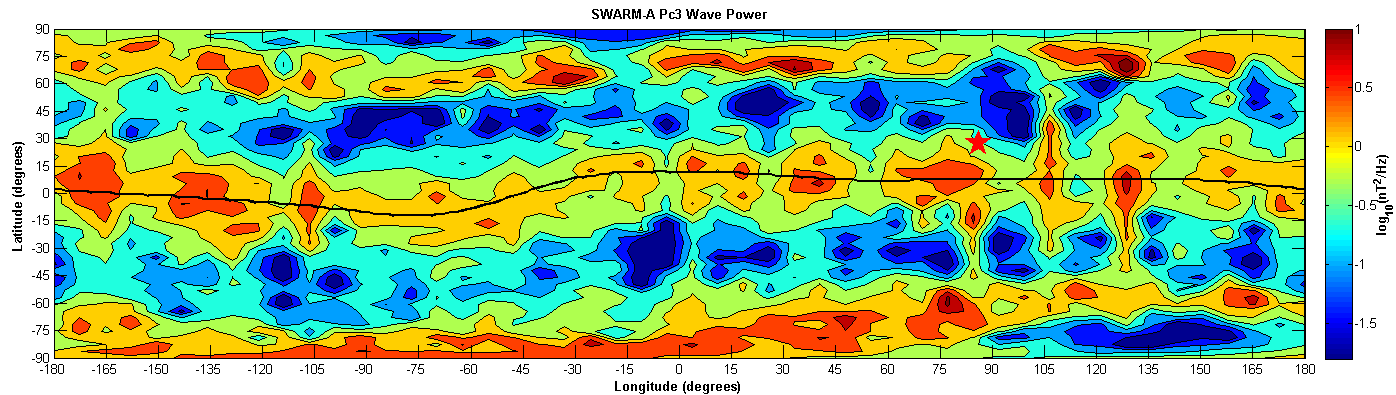
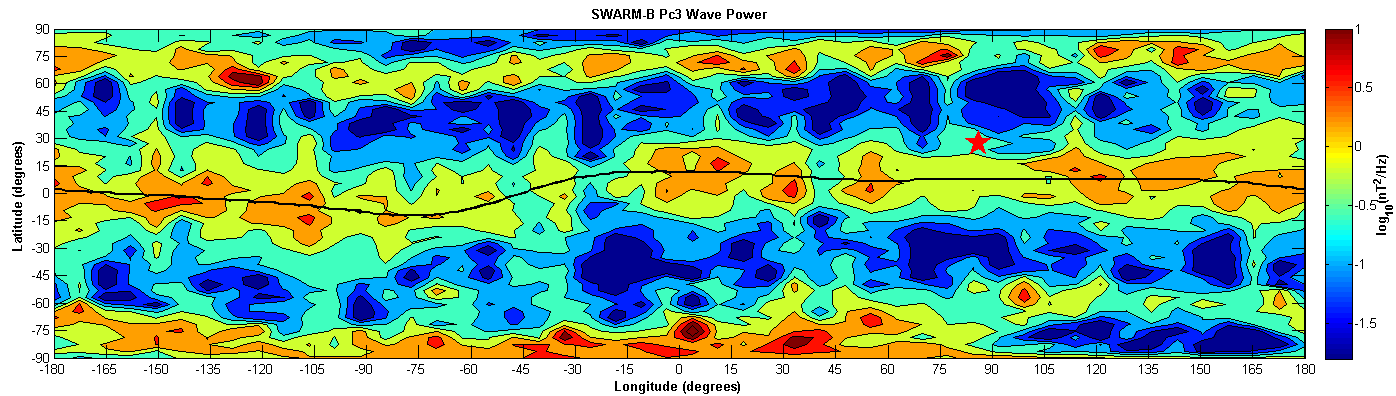
The magnetogram plot shows three data series: ΔB_x (black line), ΔB_y (blue line), and ΔB_z (red line). The y-axis is labeled $\Delta B_x, \Delta B_y, \Delta B_z$ (nT) and ranges from -160 to 100. The x-axis is labeled "Time" and shows dates from 06/22 00:00 to 06/24 12:00. A legend in the bottom right of the plot window identifies the lines: ΔB_x (black dot), ΔB_y (blue dot), and ΔB_z (red dot). Below the legend is a "Variables?" section with checkboxes for ΔB_x , ΔB_y , and ΔB_z , all of which are checked. An "OK" button is located at the bottom right of the plot window.

At the bottom of the screenshot, a Windows taskbar is visible with several open applications: Hellenic GeoMag..., Total Commande..., Skype, MATLAB R2012b, Editor - C:\libs\W..., SwarmGui_unifie..., Signal Plotter v1.5..., and BEYOND_ENIGMA. The system clock shows 2:59 PM on 16/5/2016.

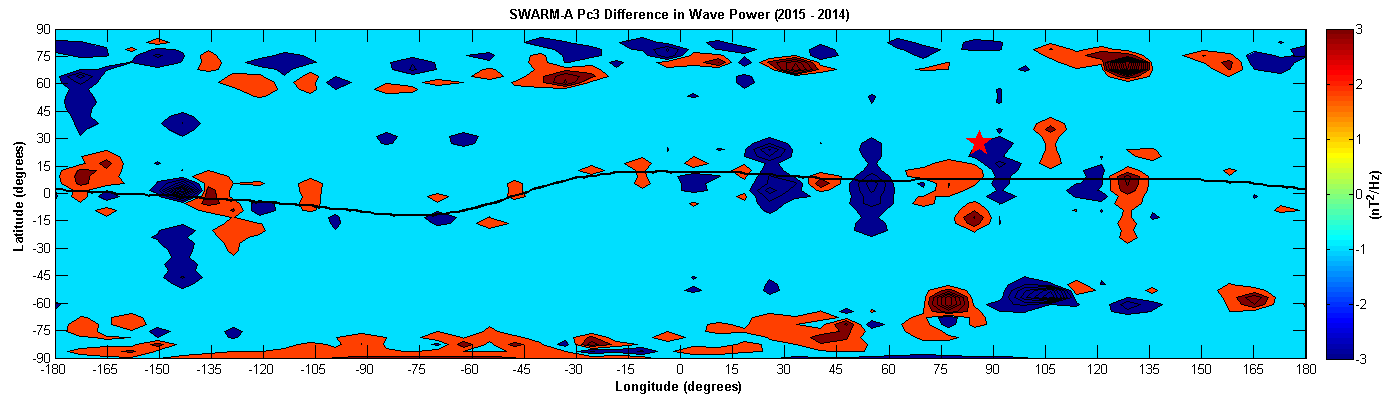
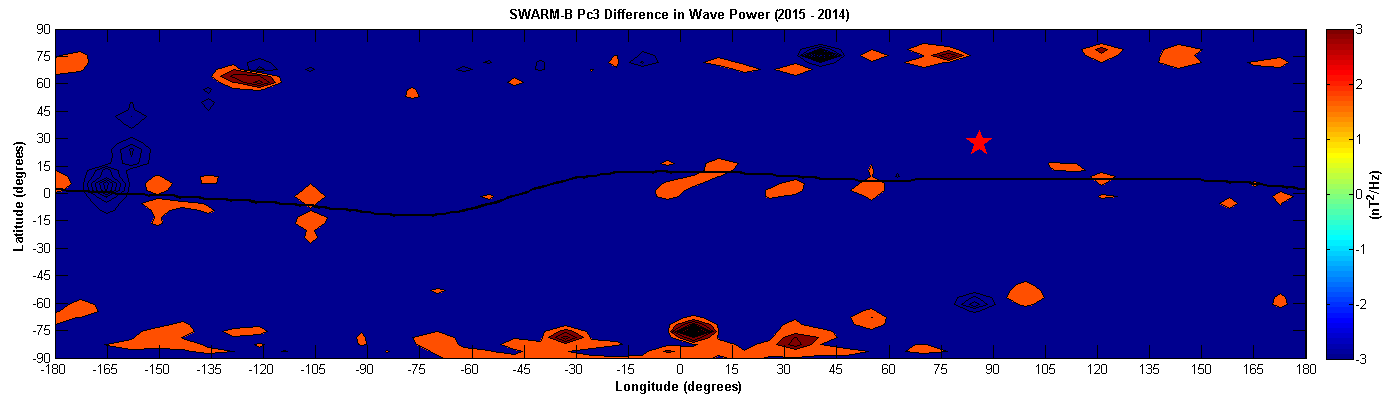
Geomagnetic data service offered by BEYOND



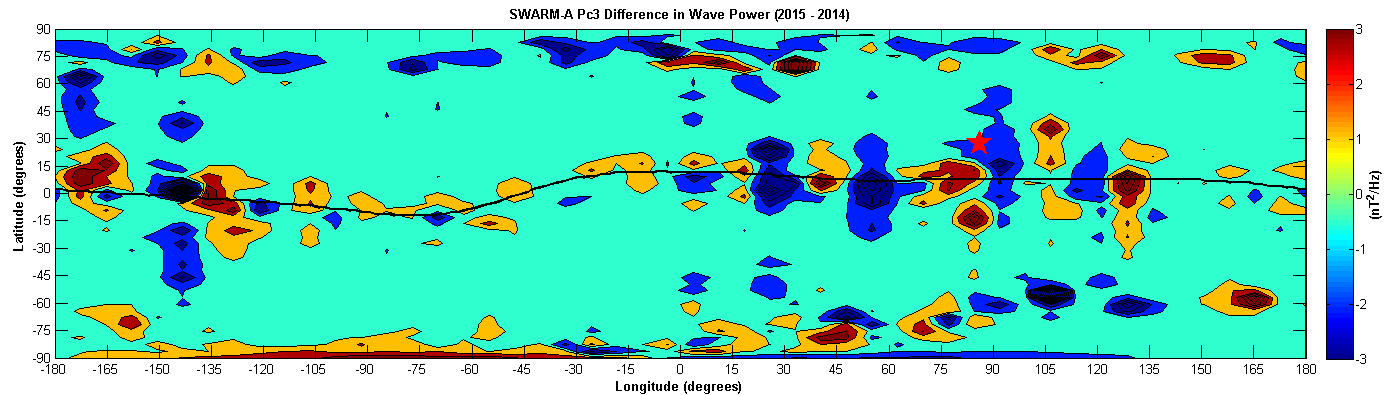
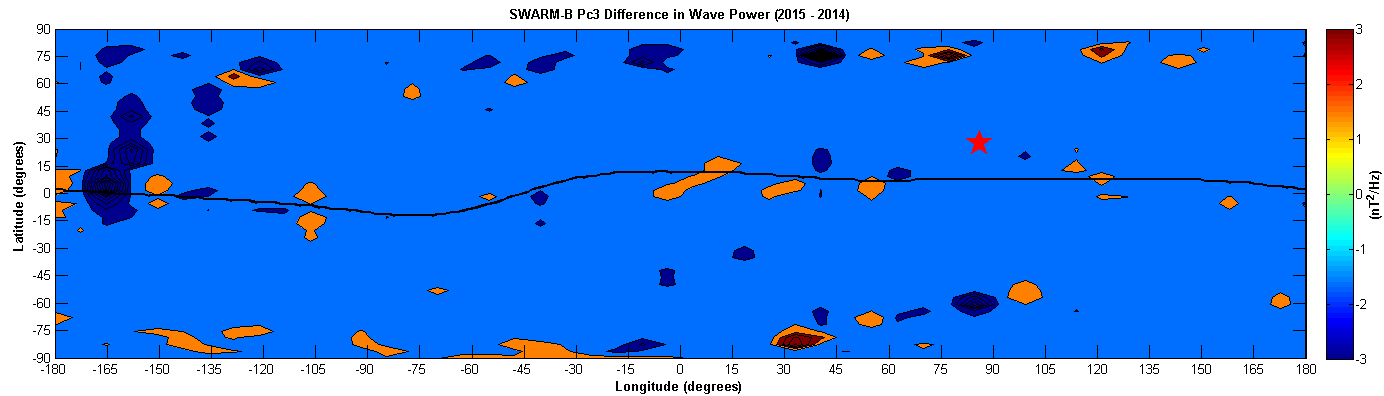
Swarm Pc3: Apr 1st – June 15th 2015



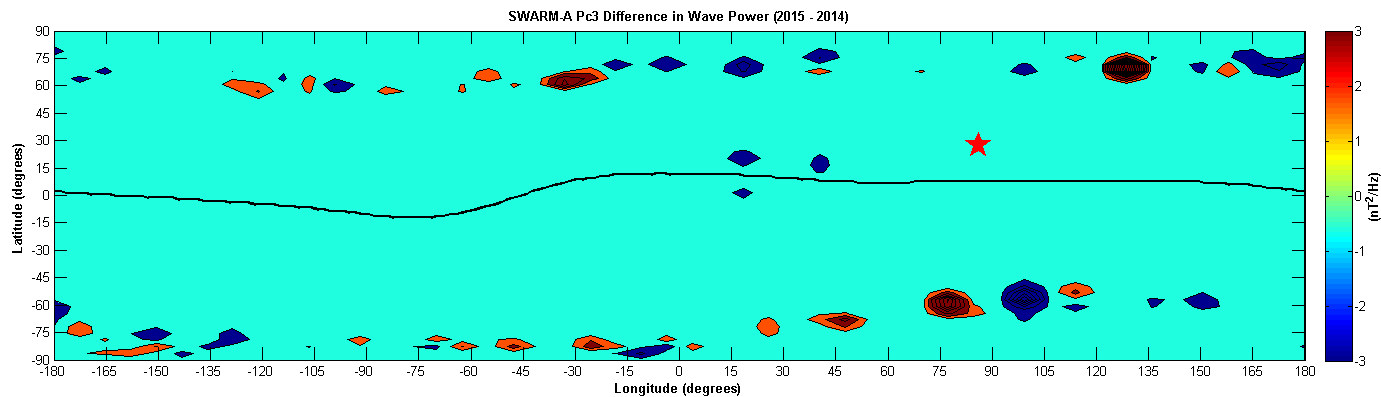
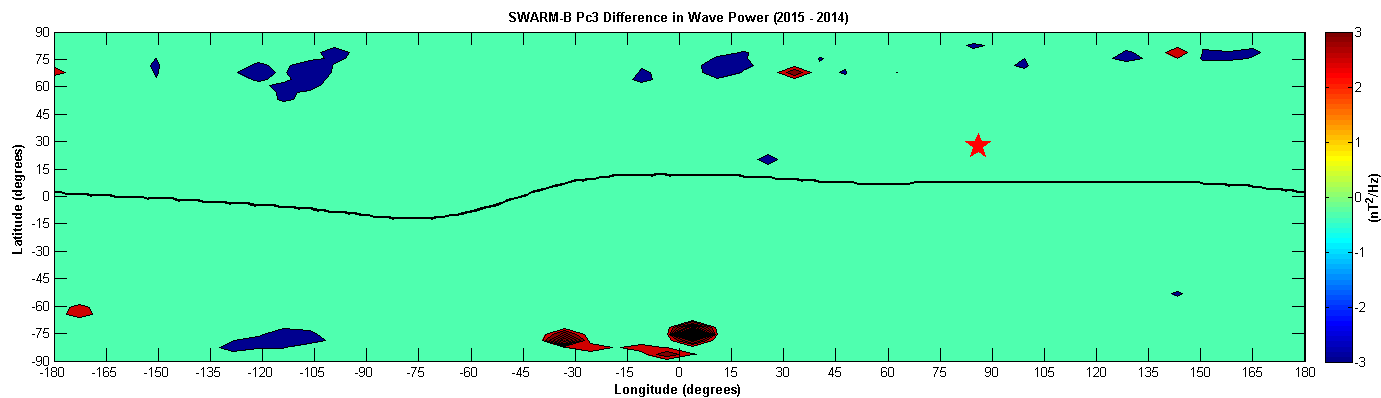
Swarm Pc3: Difference 2015 – 2014



Swarm Pc3: Difference 2015 – 2014 (Waves)



Swarm Pc3: Difference 2015 – 2014 (Instab.)



Future work

- Perform a systematic study of ENIGMA data around large EQs occurred in Greece over the last 5 years or so.
 - Test alternative time series complexity measures as well.
- Perform a systematic study of Swarm data around strong EQs occurred all over the world after Swarm's launch (11/2013).
 - Collaborate with A. De Santis (INGV, Italy) in ESA's "SAFE" project.
- Analyze ENIGMA and Swarm data around EQs occurred in Greece during the Swarm lifetime.



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Hellenic GeoMagnetic Array

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