ESA funded Project under the STSE Swarm + Innovation Programme

funded by Italian Space Agency

Pre-earthquake signatures in ionosphere as detected by Swarm satellites

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Outline

1. SAFE Project: Generalities & Swarm Mission

2. Methods and Evaluations

3. Random or EQ-related anomalies?

4. Worldwide statistics of Ne and B

5. Conclusions

Ne= electron density
B =magnetic field

Outiline

1. SAFE Project: Generalities & Swarm Mission

1. SAFE: Generalities

SAFE
Swarm for earthquake study

stse
support to science element

esa

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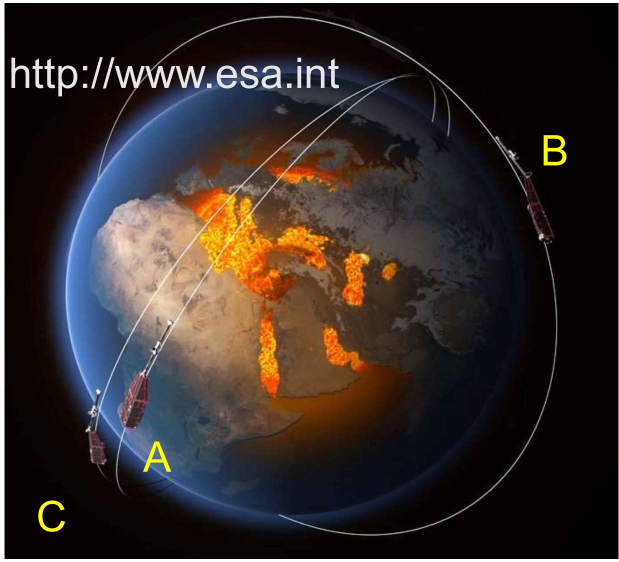
- **SAFE** (**S**warm **f**or **E**arthquake study) aims at searching **pre-EQ signals** due to the **lithosphere-atmosphere-ionosphere coupling (LAIC*)** in **Swarm satellites and other kinds of data**

- Systematic, multiparameter & multi-platform approach to study the **possible effects** (at satellite altitude and ground) of the **slow preparation process in the lithosphere** that leads to the EQ.

- Main scientific Objective: Defining Methods for LAIC detection and **Understanding the physics** behind the LAIC



Swarm 3-satellite mission
Launch on 22 Nov. 2013
A,C at 440 km (now)
B at 510 km
Appropriate combination of (em & particles) sensors

Project Website: **safe-swarm.ingv.it**
On **Researchgate**, too

* Pulinets & Ouzonouv, 2011

1. SAFE Project: the vision

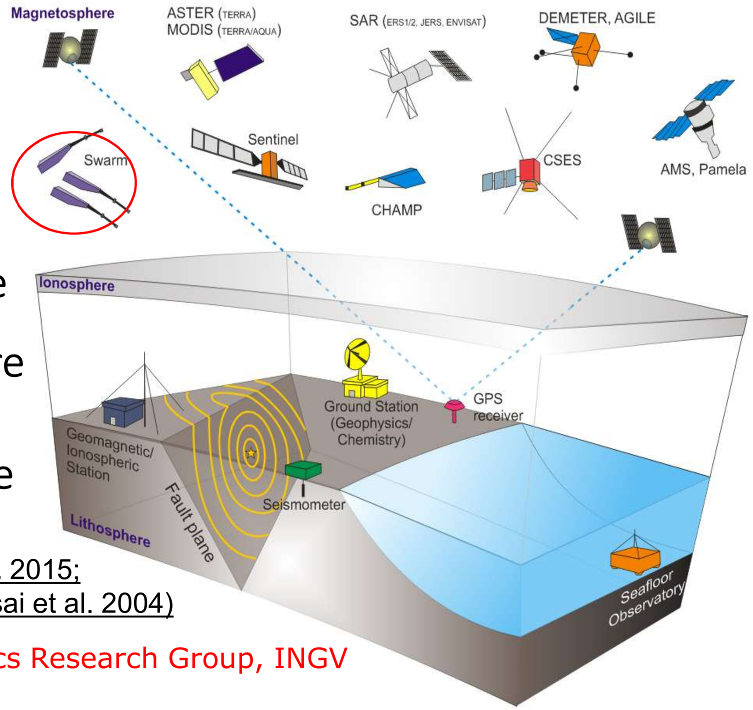
1. SAFE Project: The vision

Geosystemics[1], an integrated holistic vision

Ionosphere

Atmosphere

Lithosphere



(De Santis et al. 2015; adapted from Tsai et al. 2004)

•Geosystemics Research Group, INGV

The goal is not EQ Prediction, nowadays impossible, but to understand **the process of earthquake preparation and **geospheres coupling** based on the Lithosphere-Atmosphere-Ionosphere Coupling (**LAIC**).

Patterns in the EQ preparation phase:**

3. **Ionospheric anomalies**
   (short term)
   (from satellites or ionosondes or GPS)
   - Swarm **magnetic field**
   - Swarm **ionospheric density**
   - **Ionosonde parameters**
   - **TEC** (GPS based)

2. Atmospheric anomalies
   (short term)
   - Thermal/WV/O3 anomalies

1. **Seismic & Magnetic field fore-patterns**
   - Acceleration (S-Shape)

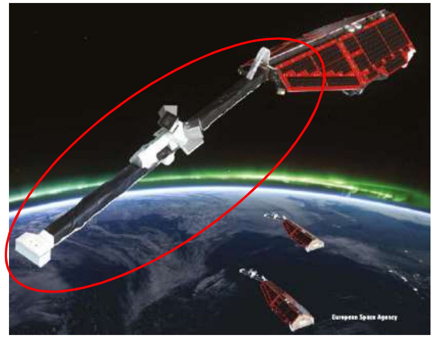
SAFE Project 2015/16

SAFE Project –extension 2018/19

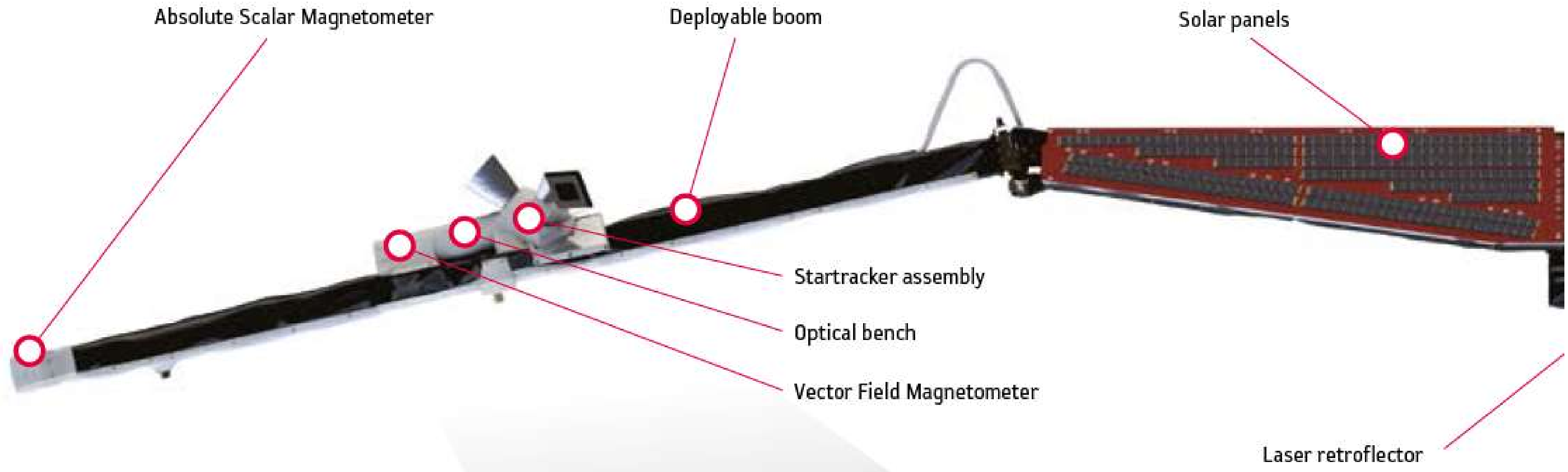
[1] De Santis 2009, 2014; De Santis & Qamili, 2015; De Santis et al., 2015, 2019

Swarm Mission

Swarm satellites:
the sensors at the back



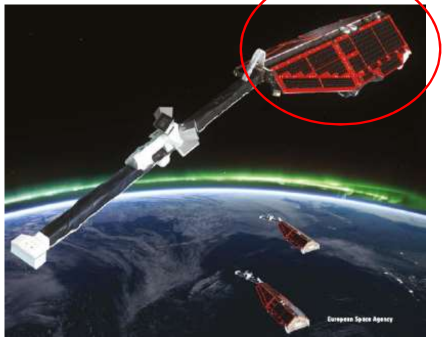
The sensors represent the cutting edge technology in their field

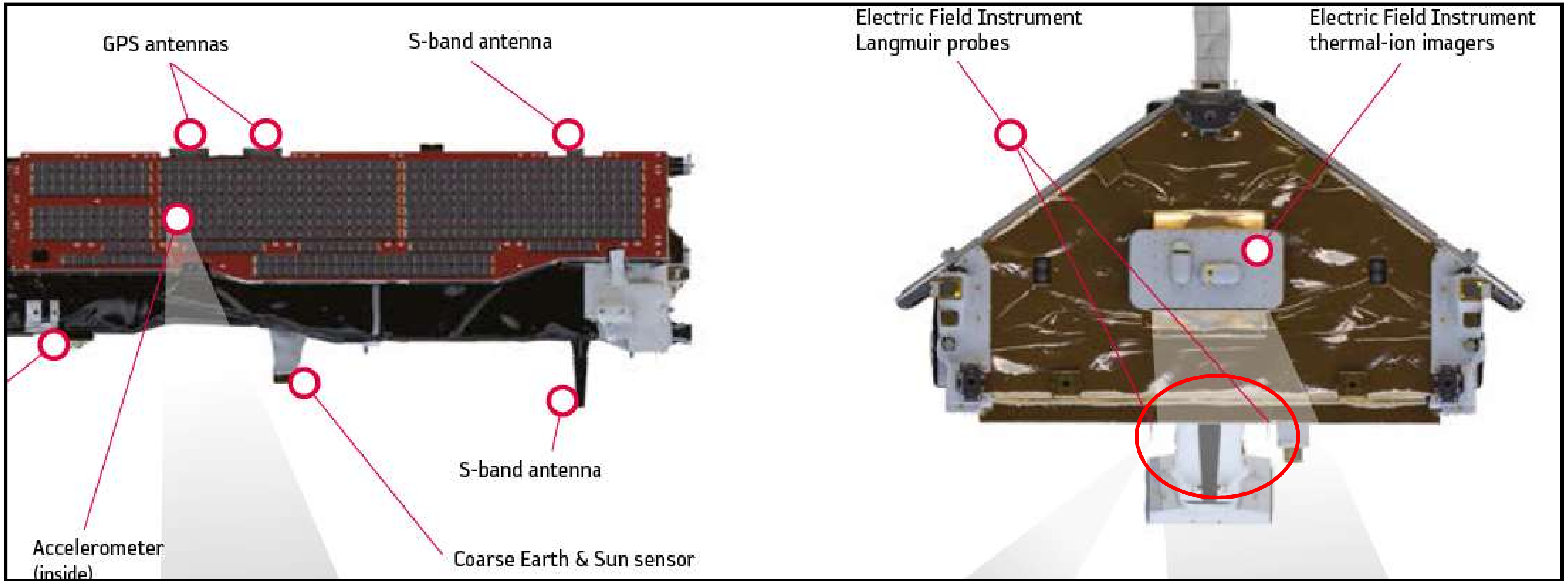


Scalar[1] & Vector Field[2] Magnetometers

[1] Optically-pumped metastable helium-4 magnetometer [2]Ring core fluxgatemagnetometer

Swarm:
the sensors at the front





Swarm Mission

Accelerometer, GPS & S-band Antennas, and Electric Field instruments

Pre-EQ anomaly detection: Methods & Evaluations

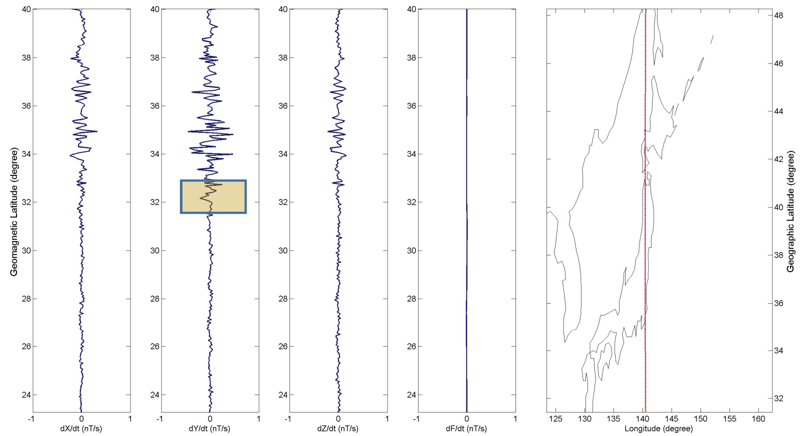
2. Methods & Evaluations

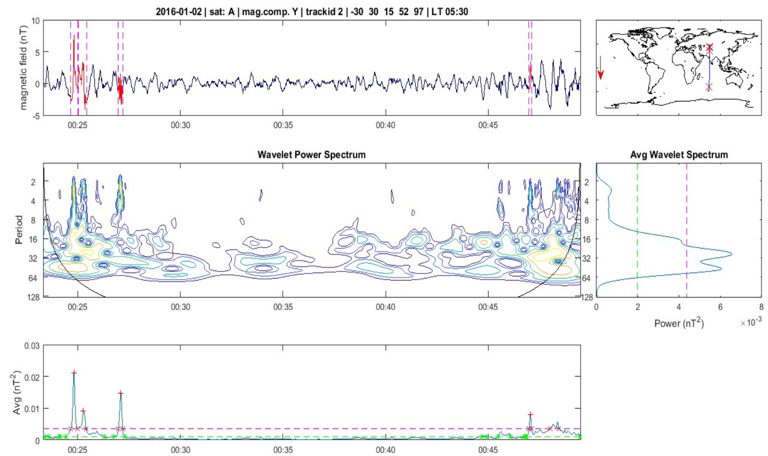
1. **Single case studies**
   - **single anomaly detection (B=mag.field, Ne=elec.density)**
     thresholds $k_t(t)$,$k_{FFT}(f)$ (t,f=time,frequency domain)
   - **pattern detection**
     S-shape cumulative number of anomalies
2. **Worldwide statistics**
   - **Real anomalous data (B/Ne) vs EQs analyses**
   - **Random anomaly simulations vs real EQs analyses**

Automatic detection of magnetic/electron density anomalies

Two different methodologies:

- **MASS algorithm** → **RMS**, **Frequency**
- **WARP algorithm** → **Location**, **Frequency**, **Duration**, **Energy**





MASS = MAgnetic **S**warm anomaly detection by **S**pline analysis
WARP = Wavelet **A**nomaly **R**esearch **P**rogram

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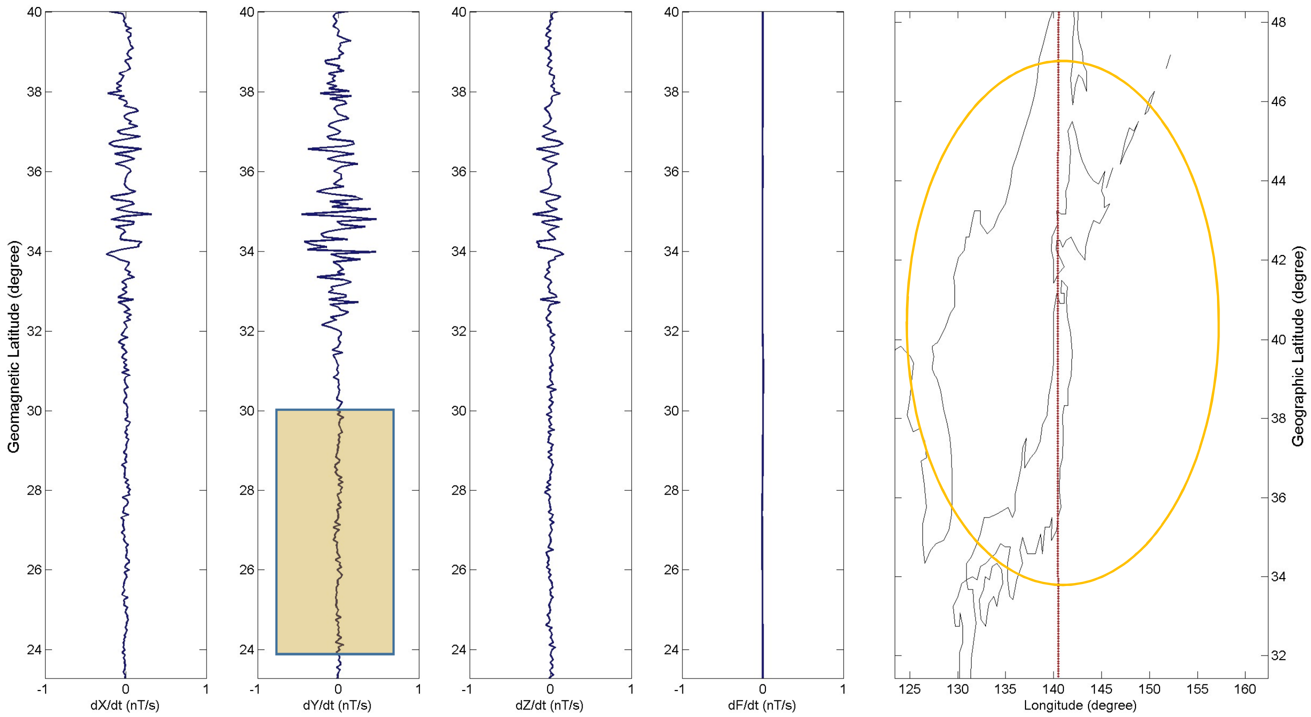
Automatic detection of anomalies: MASS algorithm

MASS = MAgnetic **S**warm anomaly detection by **S**pline analysis

1. **Estimation of the Root Mean Square (RMS) of the whole track (±50° geomag. lat.)**
2. **Calculus of rms in a moving small window of 7.0° (settable) in an area (Dobrovolsky area, area with fixed radius)**
3. **An output file reports how many windows with rms > k_t x RMS are found for each magnetic component + scalar intensity for each track during magnetic quite time (|Dst| ≤ 20 nT and ap ≤ 10 nT)**



Automatic detection of anomalies: MASS algorithm

SAT.:B.Y/M/D:2015/2/11. Track n.:20 U.meanLT:0:17:12,meanUTC:14:55:28, Dst=-12nT, ap=9nT
Flag_F: 1030 Flag_B: 0 Flag_q: 0 Flag_platform: 1030 point number : 1030

1. **Estimation of the Root Mean Square (RMS) of the whole track (±50° geomag. lat.)**
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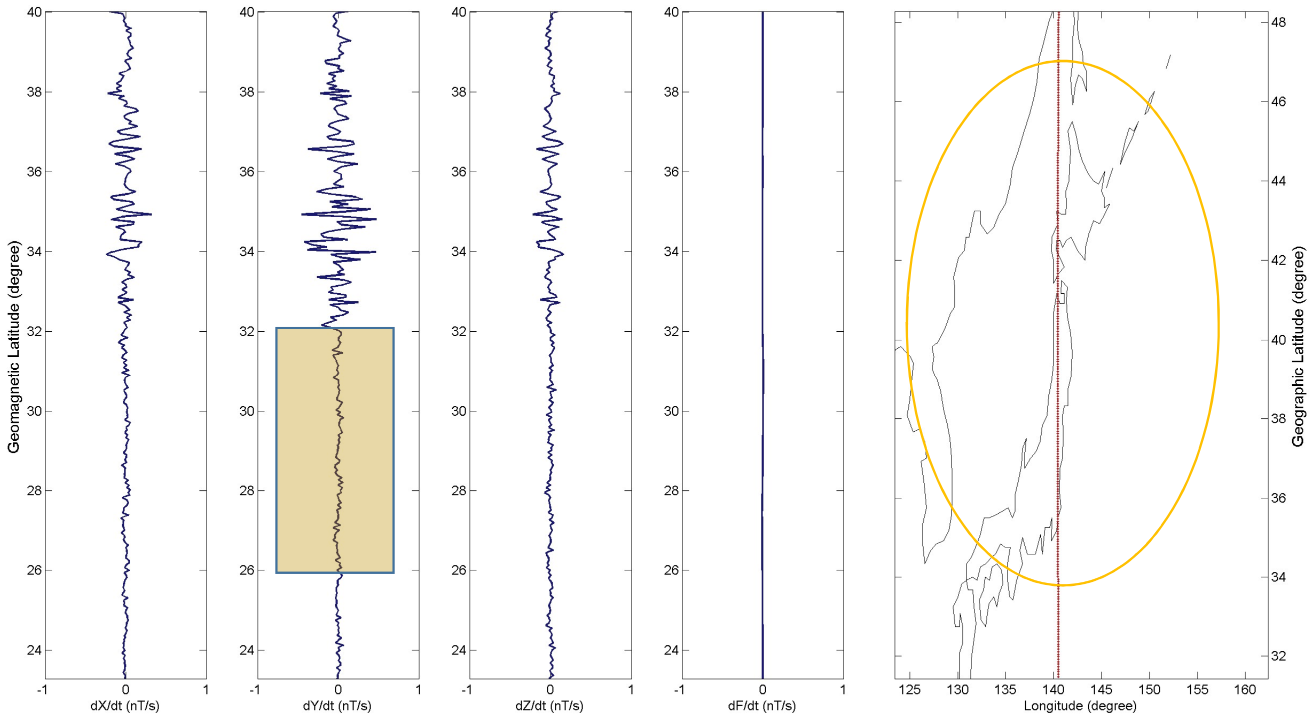

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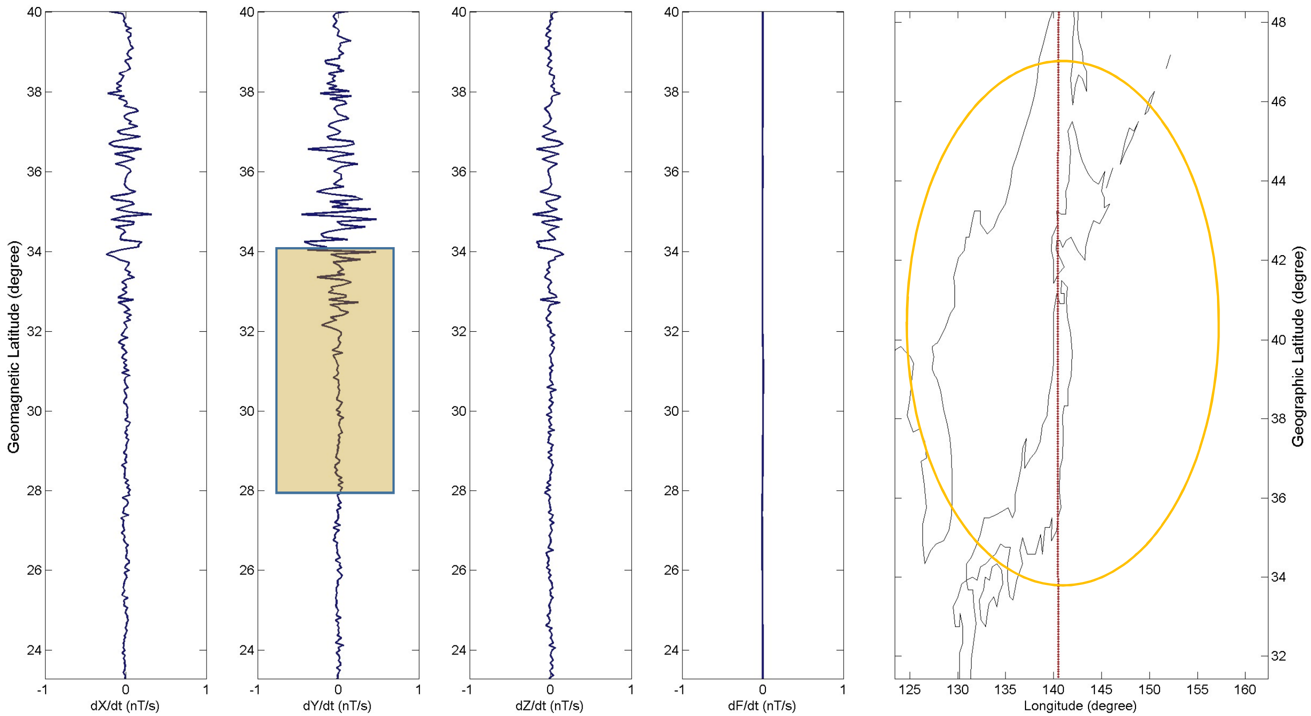

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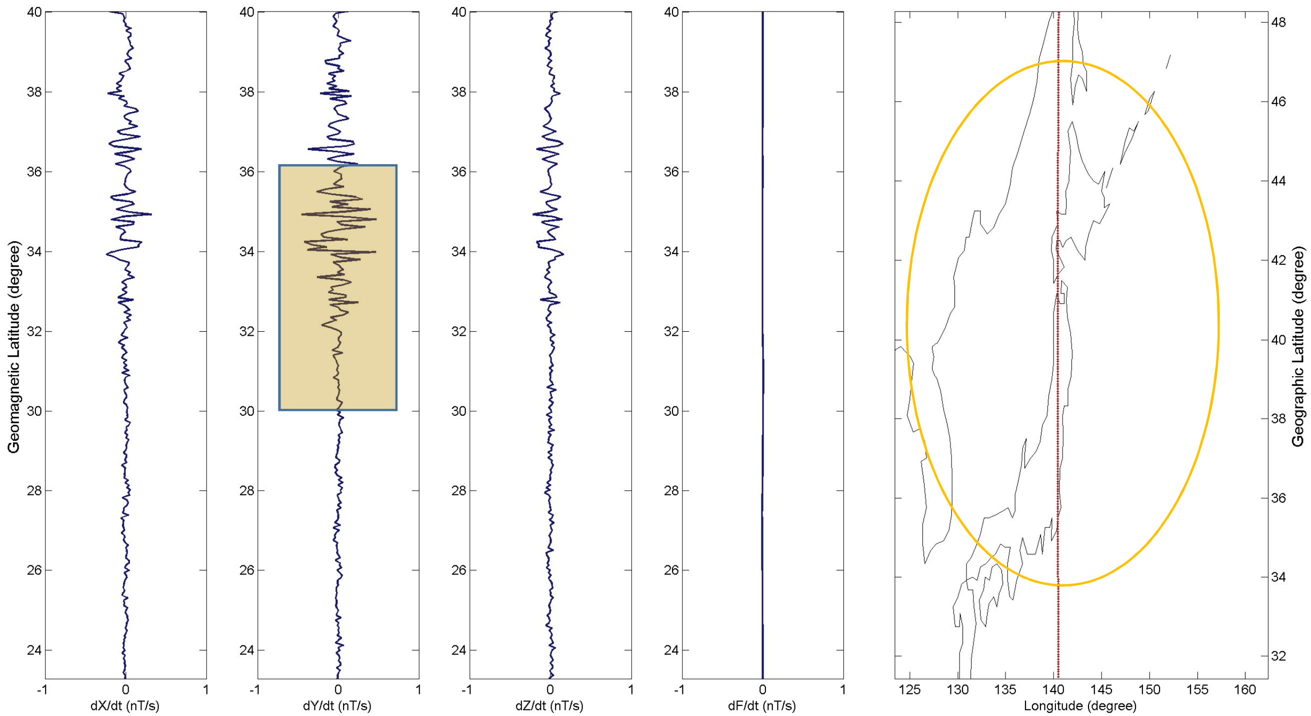

Automatic detection of anomalies: MASS algorithm

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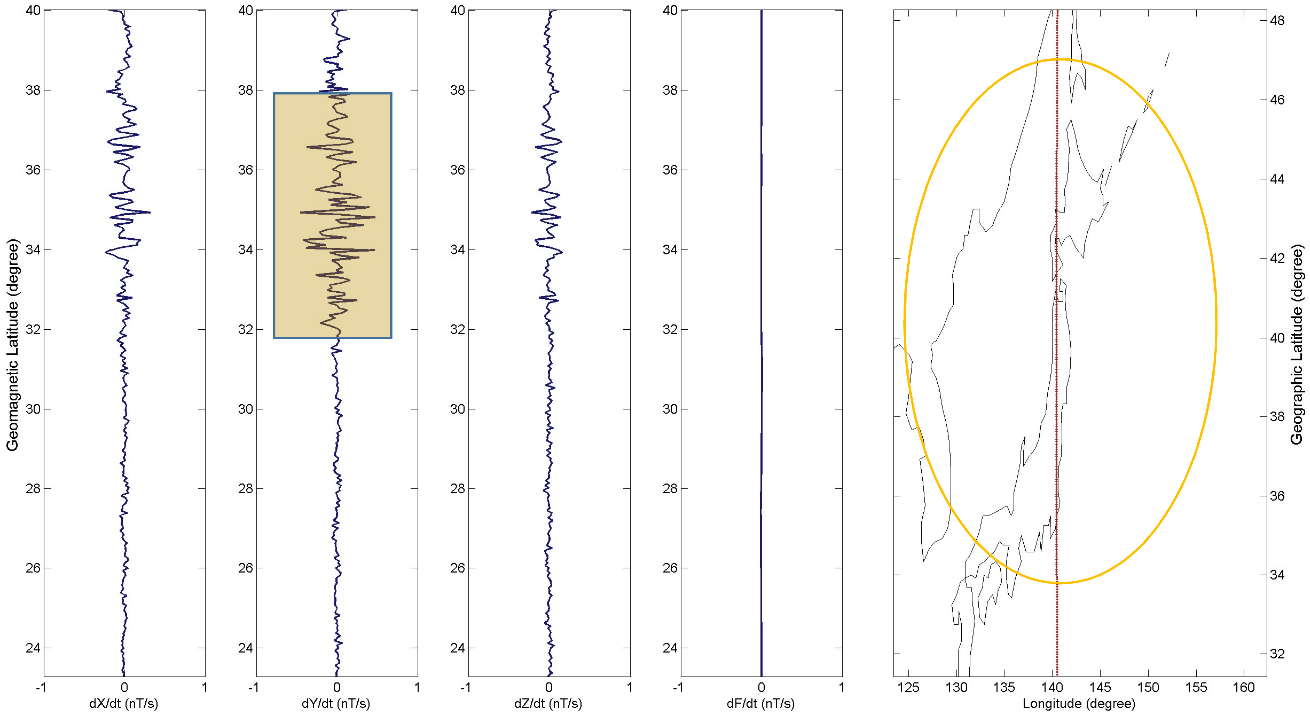

Automatic detection of anomalies: MASS algorithm

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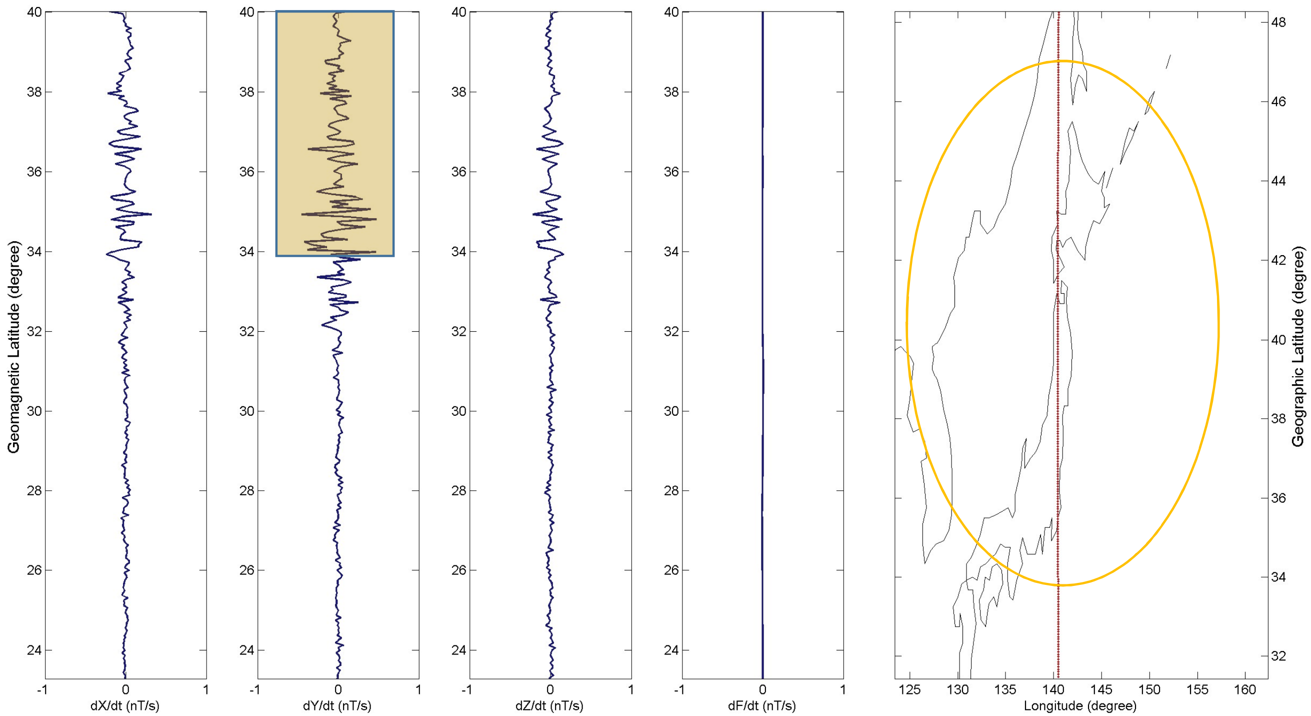

Automatic detection of anomalies: MASS algorithm

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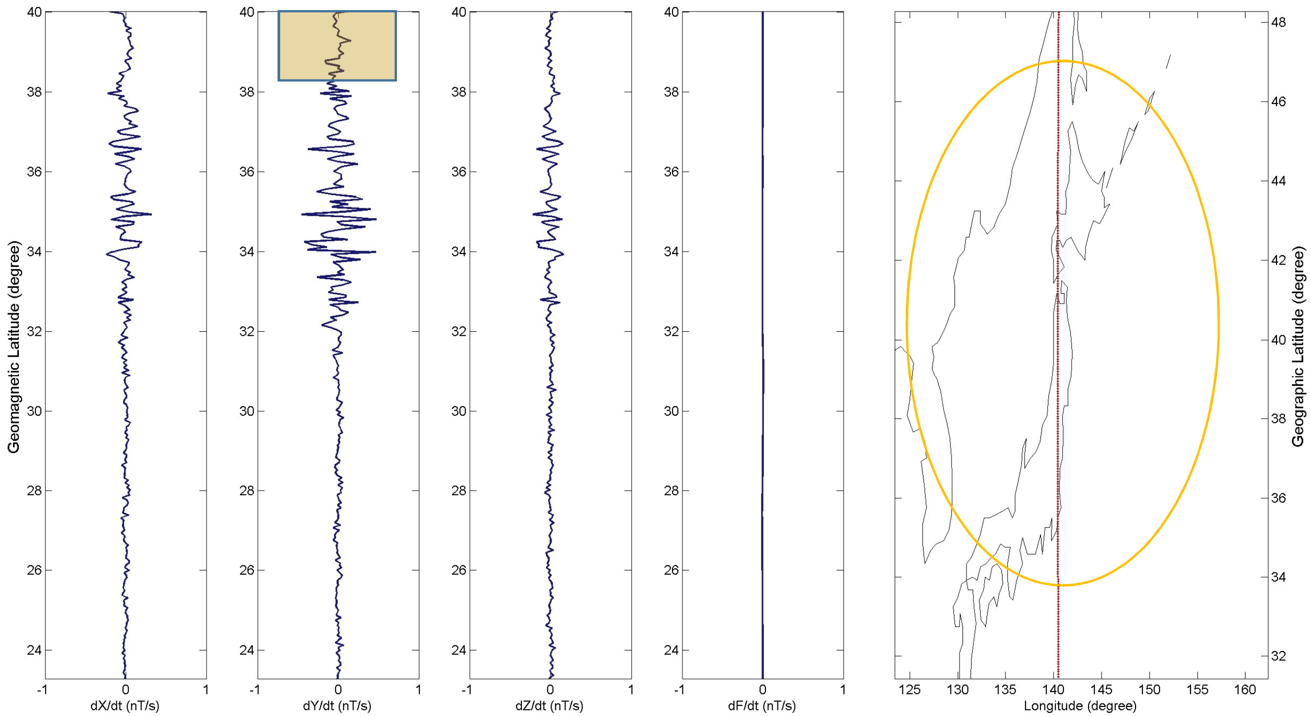
k_t =3.0 for Ne
k_t =2.5 for B_y

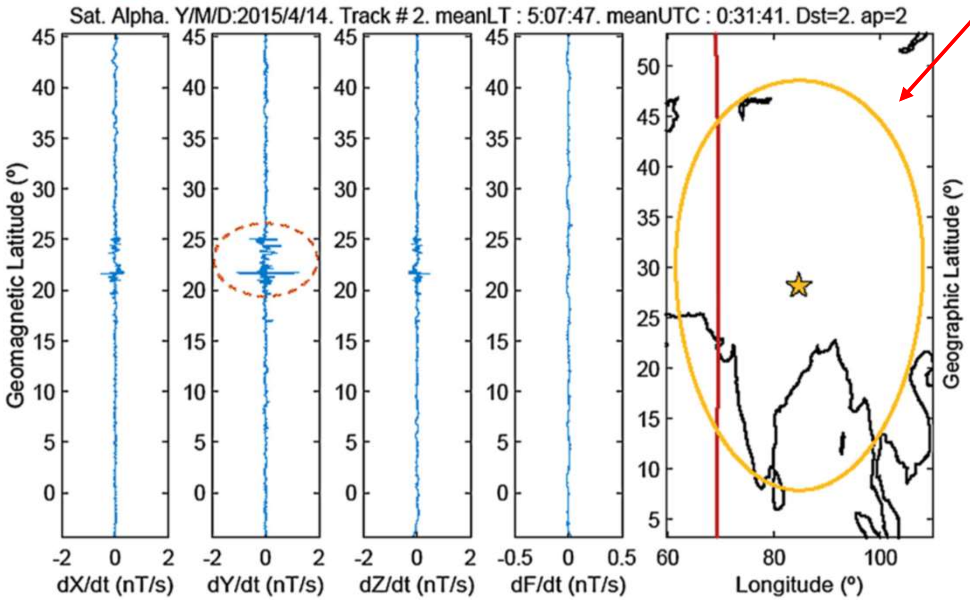


Search for single anomalies & patterns

Case study: M7.8 Nepal 25 April 2015 06:26UT

2. Methods & Evaluations

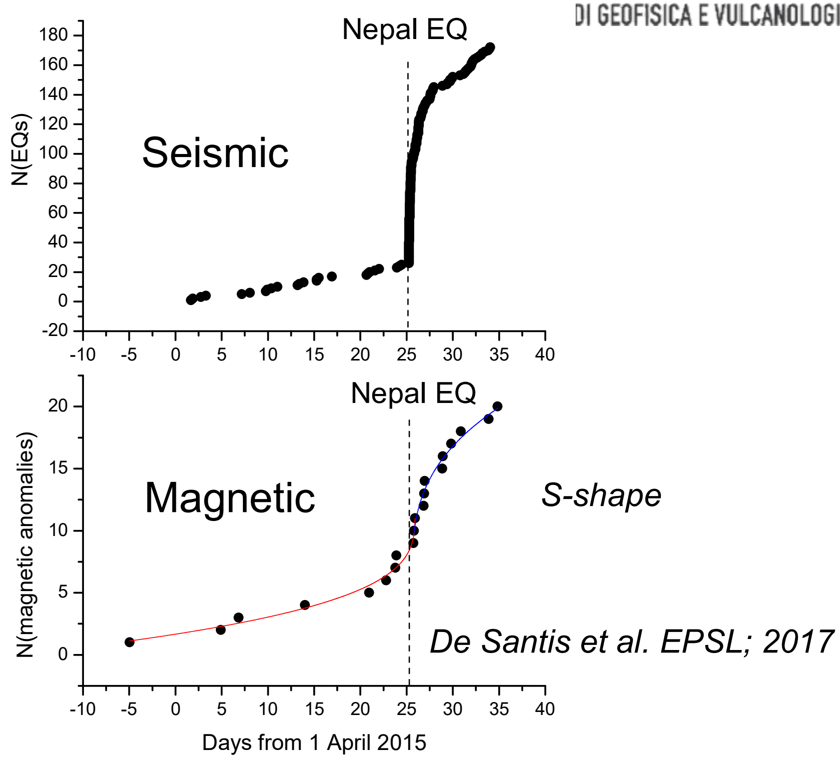
Dobrovolsky (1979) area:
R (km) = $10^{0.43M}$ = 2250 km



dX/dt, dY/dt, dZ/dt, dF/dt, geogr. map

Alpha satellite (460 km)

rms>k_t*RMS (k_t =2.5)



Cumulative # EQs and of magnetic anomalies during night & magnetic quiet times

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Retrospective Multi-parameter Analyses

AMR: Accelerated Moment Release
MASS: MAgnetic Swarm anomaly detection by Spline analysis
NeSTAD: Electron Density Single Track Anomaly Detection
NeLOG: LOGarithm of electron density anomaly detection

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2. Methods & Evaluations

Evaluation of methods (1/2)

-------------Magnetic-------------- -Electron Density-

		Seismology		Swarm Data					Ground Ion. Data				
	Earthquake	pre-EQ seism. activity	AMR/R-AMR	MASS	Wavelet I	Wavelet II (ULF)	NeSTAD	NeLOG	Ionosonde	GNSS	**OK**	**??**	**No**
1	Chile 2014 M8.2	Ok	Ok	??	Ok	Ok	??	Ok	Ok	Ok	6	2	0
2	N. Aegean Sea 2014 M6.9	??	Ok	??	Ok	??	No	??	Ok	Ok	4	3	1
3	Nepal 2015 M7.8	??	Ok	Ok	??	??	Ok	Ok	0	0	4	2	0
4	Chile 2015 M8.3	No	0	Ok	??	No	??	Ok	0	0	2	2	1
5	Japan 2015 M6.7	No	No	Ok	No	No	??	??	??	Ok	2	3	3
6	Japan 2016 M7.0	Ok	Ok	Ok	??	??	Ok	Ok	Ok	??	5	3	0
7	Ecuador 2016 M7.8	??	??	Ok	Ok	No	No	??	0	0	2	2	2
8	Sumatra 2016 M7.9	No	??	Ok	??	Ok	??	Ok	0	0	3	3	0
9	Crete 2015 M6.1	No	??	No	No	??	??	No	0	0	0	3	3
10	Lefkada 2015 M6.5	No	??	No	No	No	No	??	??	0	0	3	4
11	Gibraltar 2016 M6.3	??	??	No	No	??	No	Ok	??	0	1	3	3
12	Taiwan 2016 M6.4	No	Ok	Ok	??	??	No	Ok	0	0	3	2	1
	Ok/??/No		5/5/1	7/2/3	3/5/4	2/6/4	2/5/5	7/4/1	3/3/0	3/1/0			
	Evaluation:												
	ok - success		C<=0.6	S-shape		Spatial Anom.	S-shape	S-shape	Verified Anomaly				
	?? - no clear indication		0.6<C<1			No clear			Dubious Anomaly				
	No - no pattern detected		C>=1			No Spat. Anom.			No anomaly				

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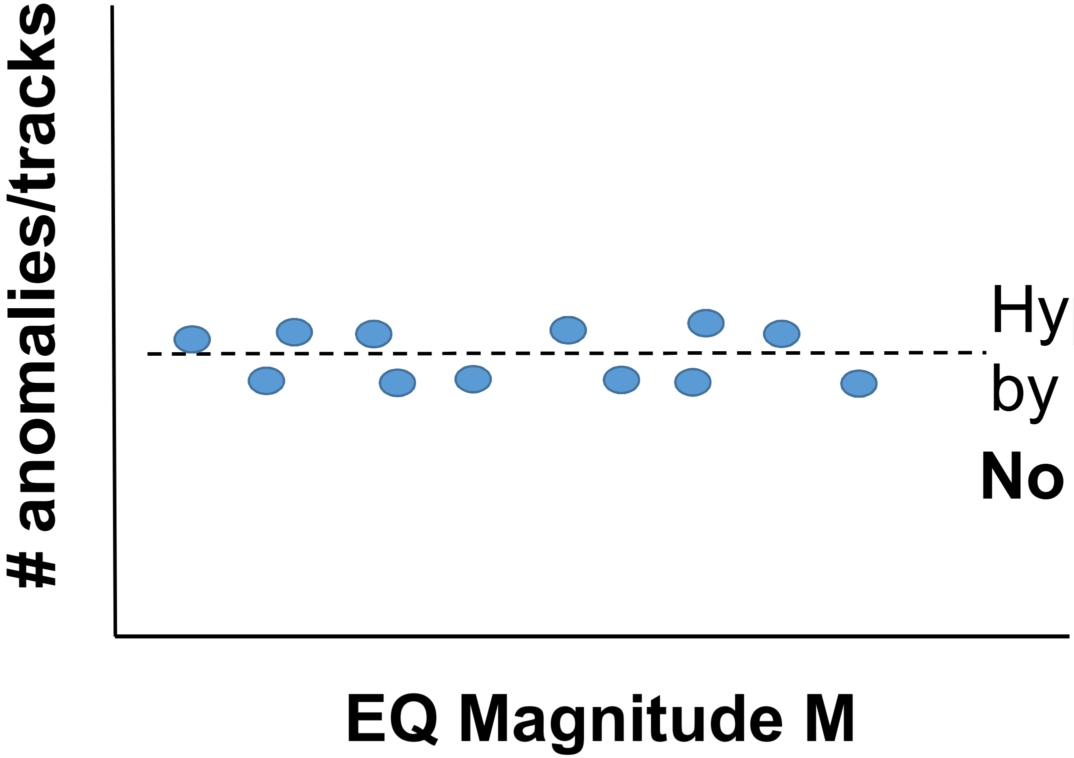
Are the anomalies found in the 12 case studies random or EQ-related?

i.e. FAKE or REALITY?



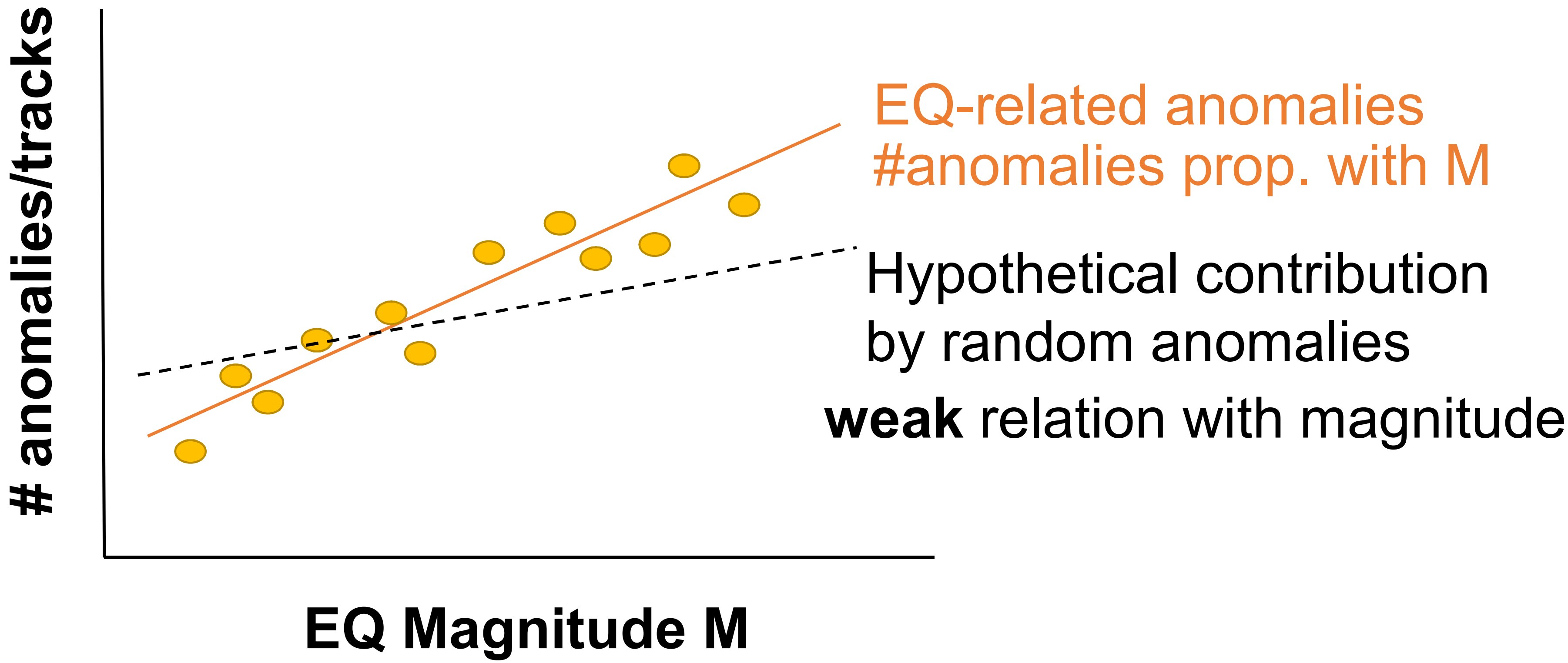
Hypothetical contribution by random anomalies

No relation with magnitude

3. Random or EQ-related?

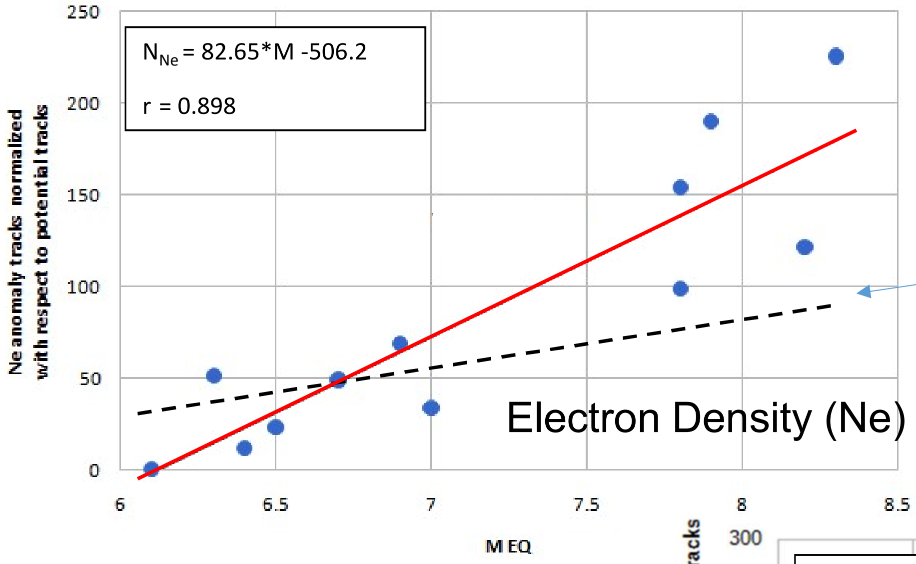
Are the anomalies found in the 12 case studies random or EQ-related?

i.e. FAKE or REALITY?



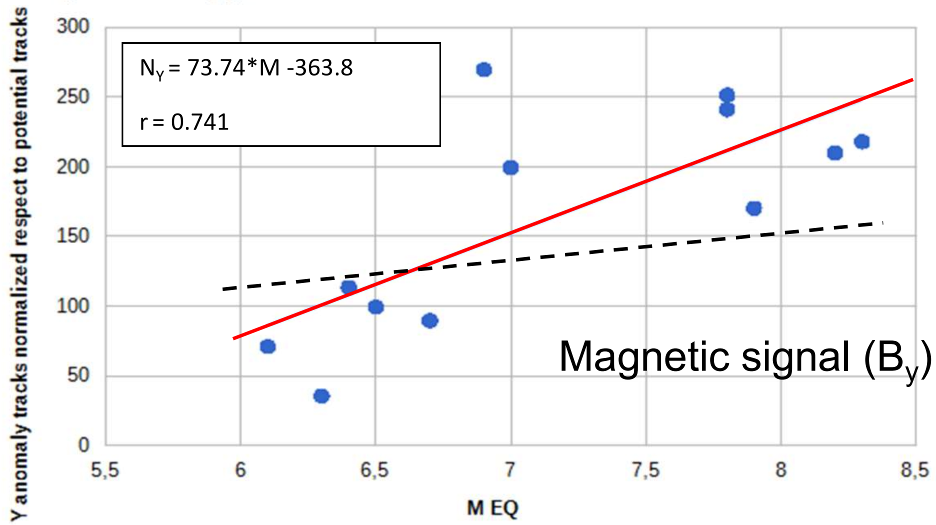
3. Random or EQ-related?

Are the anomalies random or EQ-related?



Real anomalies

Contribution
by simulated random anomalies



Normalized Number of anomalies increases with magnitude more than random simulations→ they are EQ-related!!

De Santis et al., *Atmosphere*, 2019

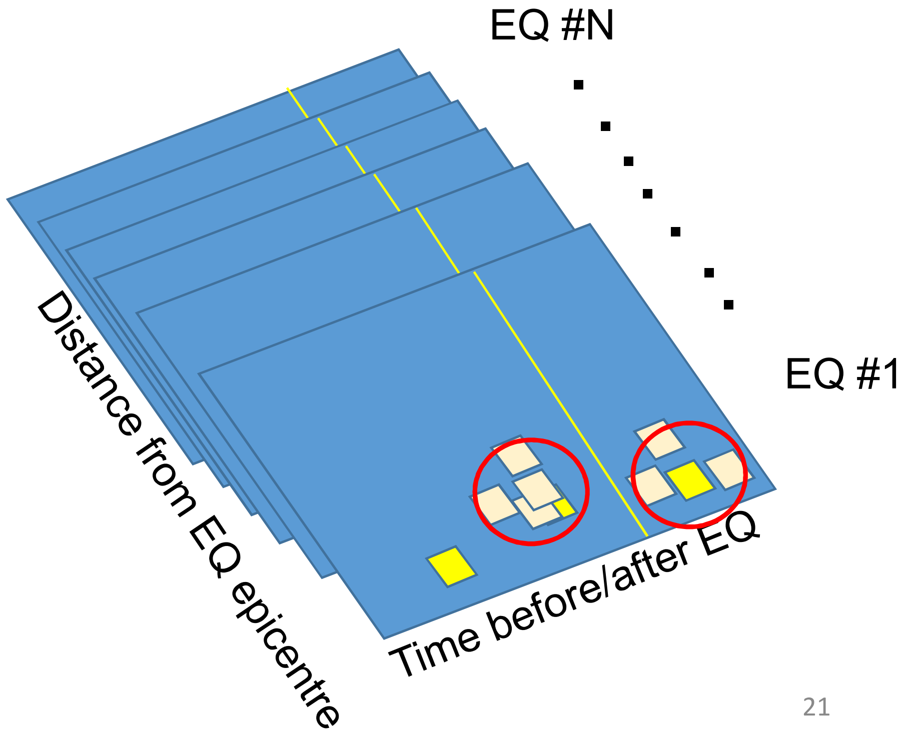
Worldwide statistics with Superposed Epoch

4. Worldwide statistics

For each EQ we draw a space/time diagram that we fill with the detected anomalies

Then we overlap all N (= #EQs) diagrams in a unique plot.

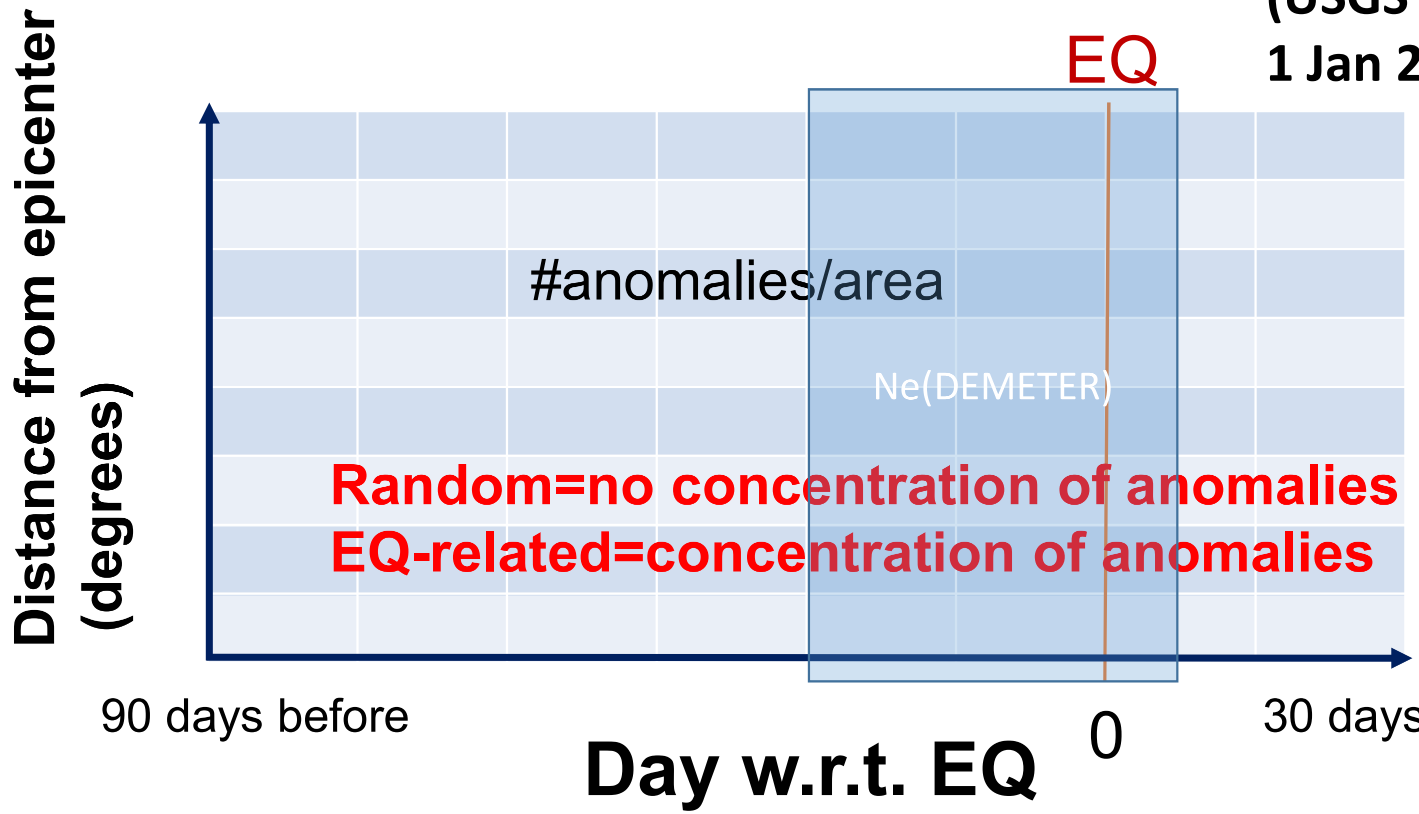
Concentrations of anomalies point out when/where anomalies usually occur (red circles)



4. Worldwide statistics

Worldwide statistics with Superposed Epoch

~ 1300 M5.5+ EQs (USGS source) 1 Jan 2014-31 Aug 2018



$$d = \frac{\left[\frac{D_{MAX}}{D_0}\right]_{real}}{\left[\frac{D_{MAX}}{D_0}\right]_{random}}$$

$$n = \frac{\left[\frac{D_{MAX}}{D_0}\right]_{real} - \left[\frac{D_{MAX}}{D_0}\right]_{random}}{\sigma_{random}}$$

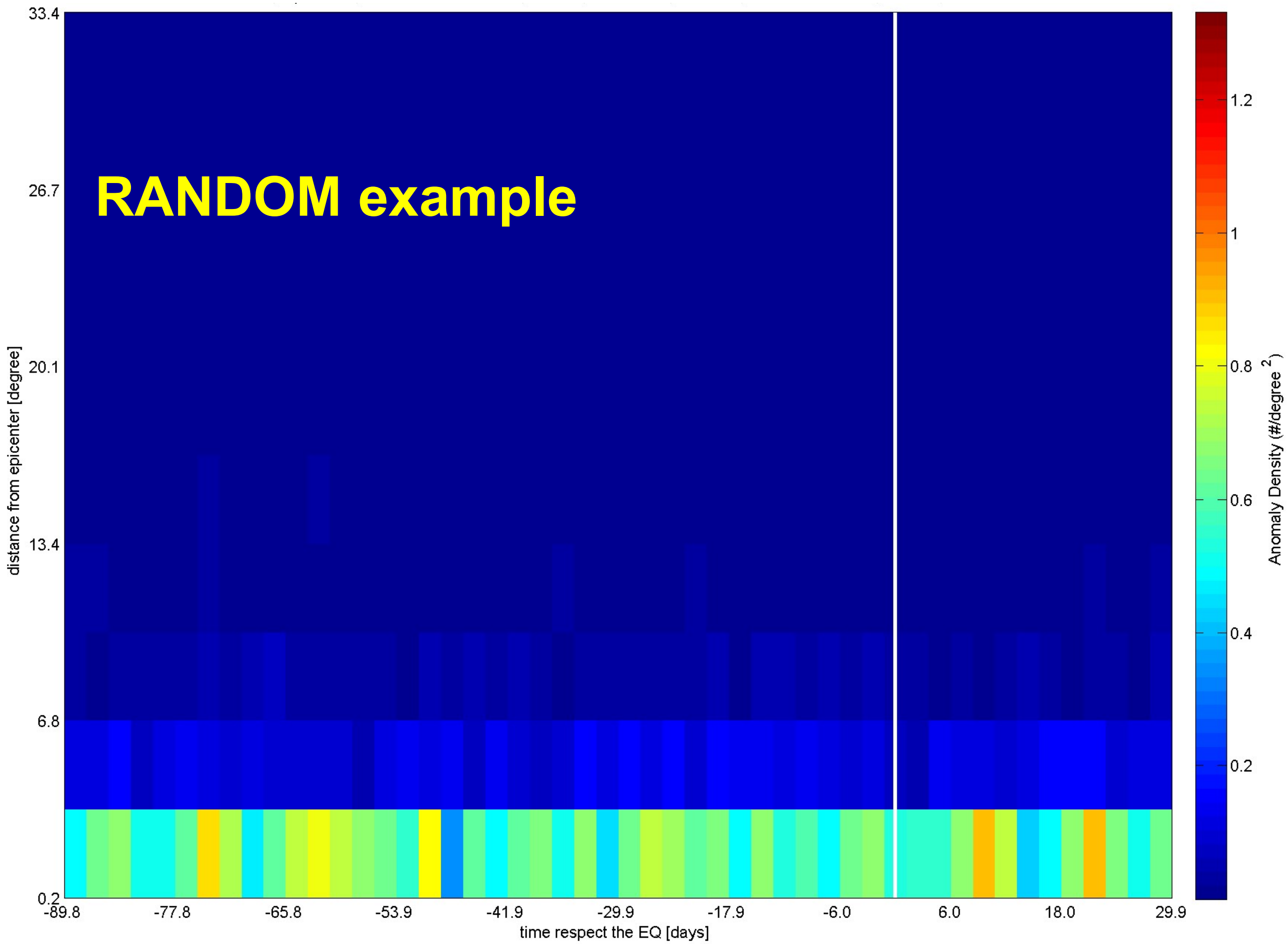
Worldwide statistics (random simulation)

4. Worldwide statistics

~ 1.3K EQs
~59K random anomalies

d≈ 1
n ≈ 1

Positive statistics if $d \geq 1.5$ $n \geq 4$



RANDOM anomaly space-time distribution

Declusterized Seismic USGS Catalog
geom. Lat. ≤ |50°|
1312 M5.5+ shallow EQs

1 Jan 2014-31 Aug 2018

A. De Santis, Pre-earthquake signatures in ionosphere, 2019 Italian URSI Meeting, Pisa, 26 September 2019

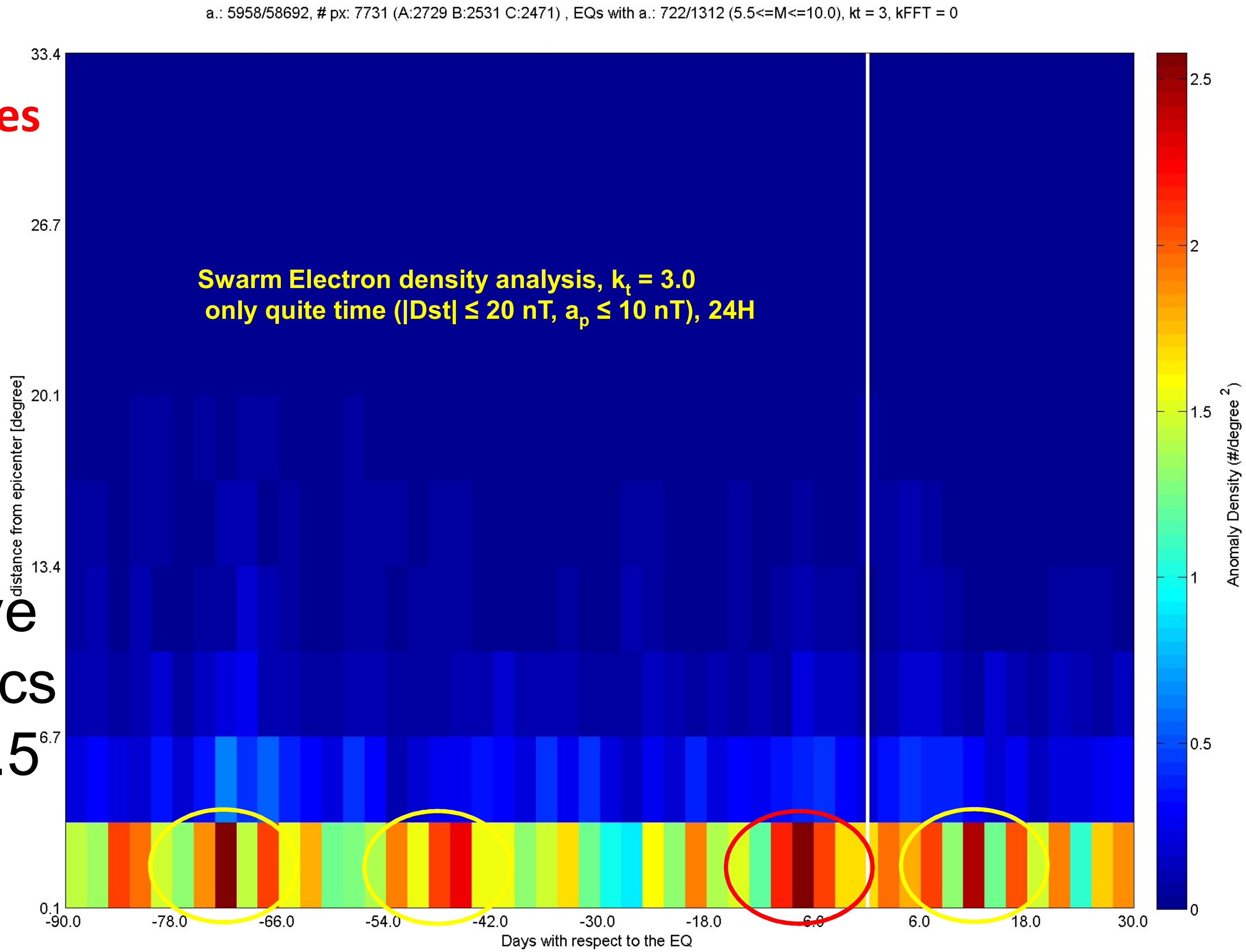
Worldwide statistics Electron Density

~ 1.3K EQs
~ 59K anomalies

4. Worldwide statistics

d=1.5
n=8.7

Positive statistics if $d \geq 1.5$
$n \geq 4$



Thresholds on Ne data
k_t = 3.0
Declusterized Seismic USGS Catalog
geom. Lat. ≤ |50°|
1036 M5.5+ shallow EQs

1 Jan 2014-31 Aug 2018

The largest maximum anticipates EQs by 4-10 days, confirming previous results by Demeter

Other larger concentrations (70-80 and 44-52 days before EQs and 10-12 days after).

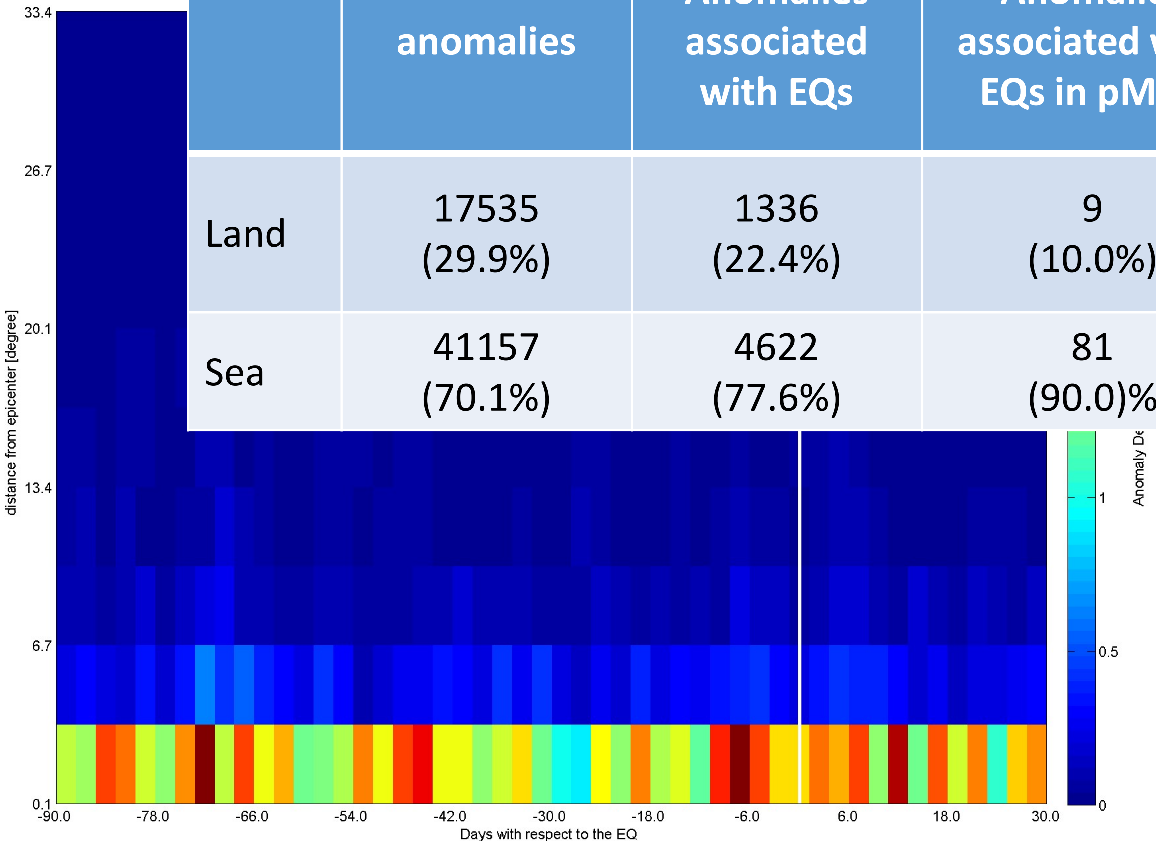
A. De Santis, Pre-earthquake signatures in ionosphere, 2019 Italian URSI Meeting, Pisa, 26 September 2019

Worldwide statistics Electron density Signal: Distribution of anomalies on land/sea

Considering k_t=3.0

Dobrovolsky (Db) area

	anomalies	Anomalies associated with EQs	Anomalies associated with EQs in pMAX	EQs	EQs with anomalies	EQs with anomalies in pMAX
Land	17535 (29.9%)	1336 (22.4%)	9 (10.0%)	243 (18.5%)	148 (20.5%)	3 (9.1%)
Sea	41157 (70.1%)	4622 (77.6%)	81 (90.0)%	1069 (81.5%)	574 (79.5%)	30 (90.9%)



Sea EQs are slightly favored

Worldwide statistics Magnetic Signal

4. Worldwide statistics

~ 1.3K EQs

~22K anomalies

Ratio between real max concentration w.r.t. random

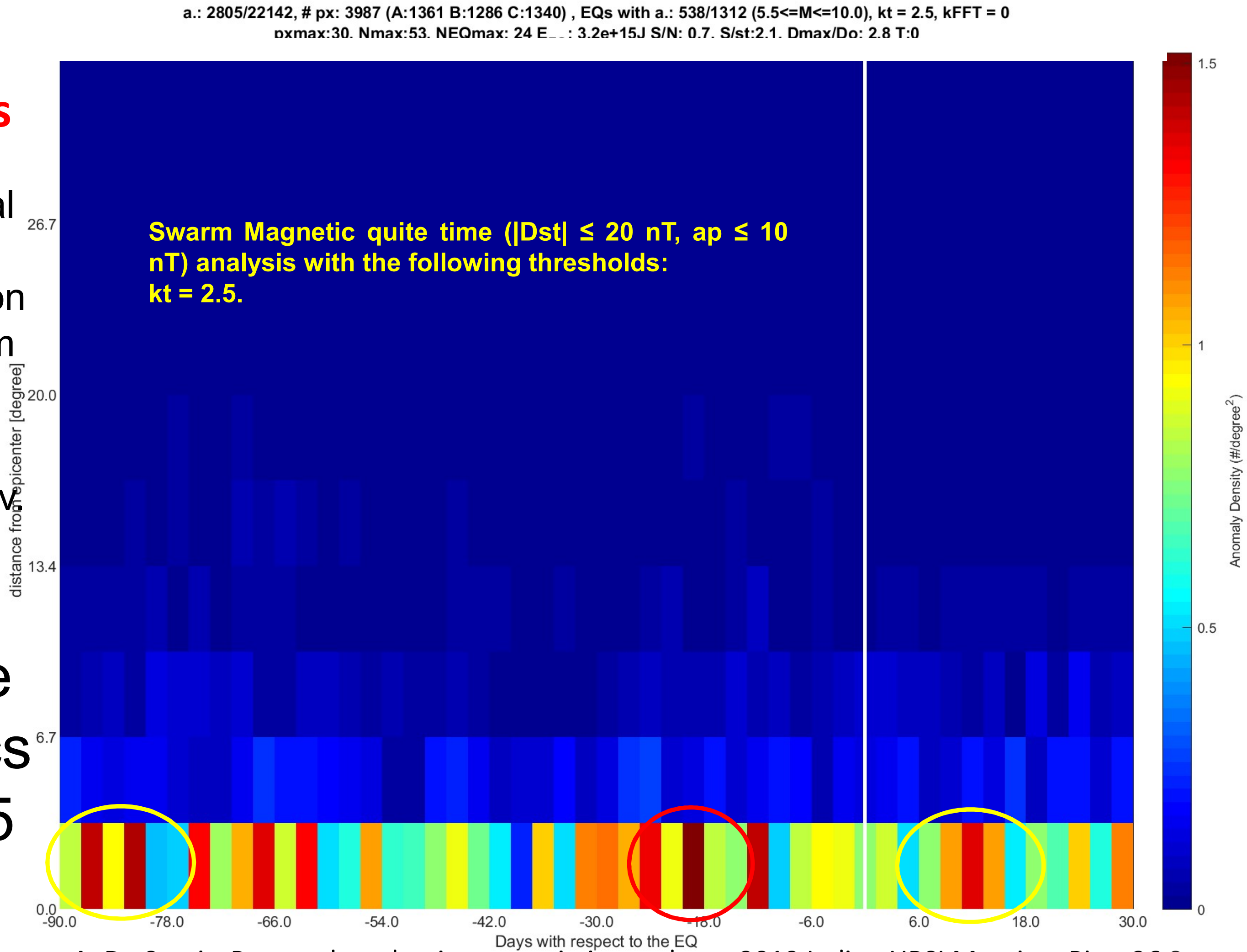
***d*= 2.0**

How many standard dev.

***n*=16.6**

Positive statistics if $d \geq 1.5$

$n \geq 4$



Thresholds on quiet magnetic data
k_t = 2.5

Declusterized Seismic USGS Catalog
geom. Lat. ≤ |50°|
1312 M5.5+ shallow EQs
1 Jan 2014-31 Aug 2018

The maximum anticipates EQs by around 20 days

Other concentrations at 85 days and after 6 days

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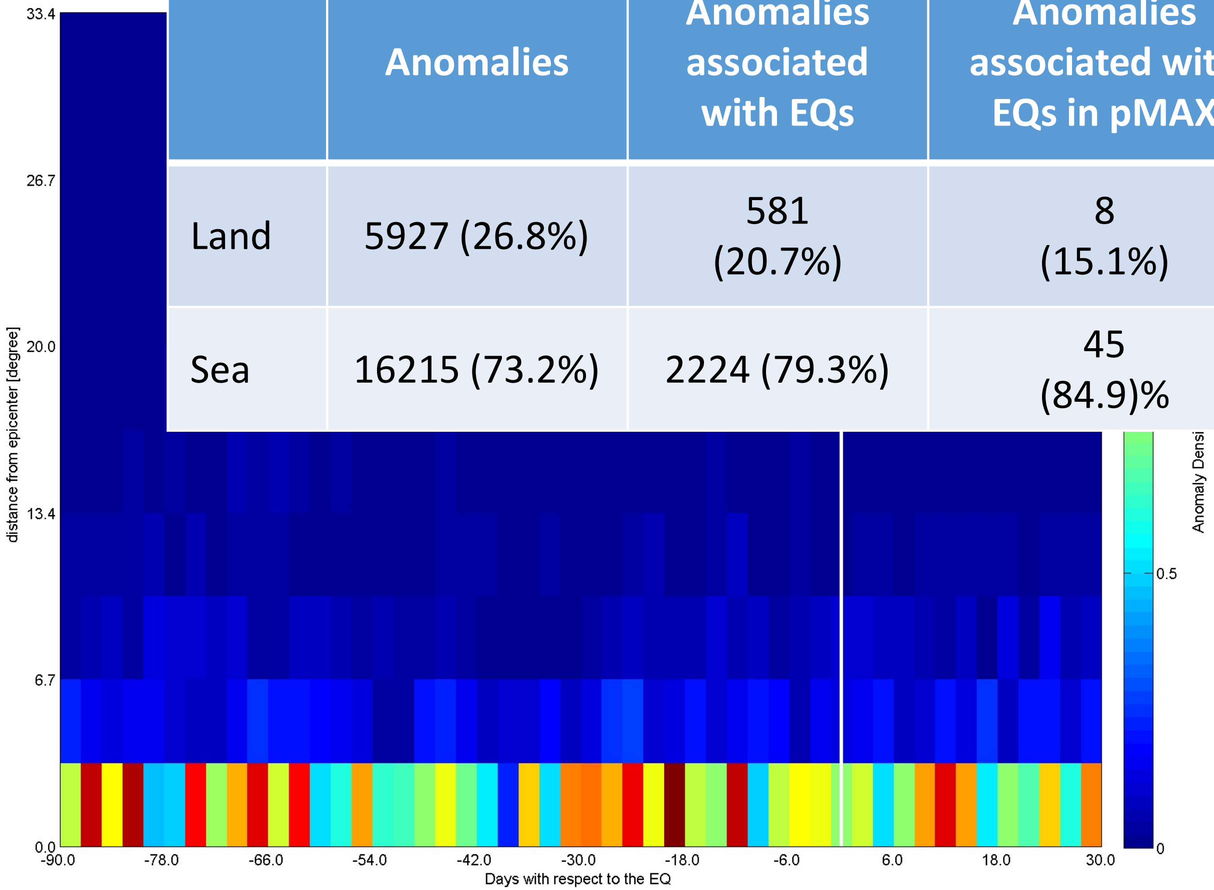
Worldwide statistics Magnetic Signal: Distribution of anomalies on land/sea

Considering k_t=2.5

Dobrovolsky (Db) area

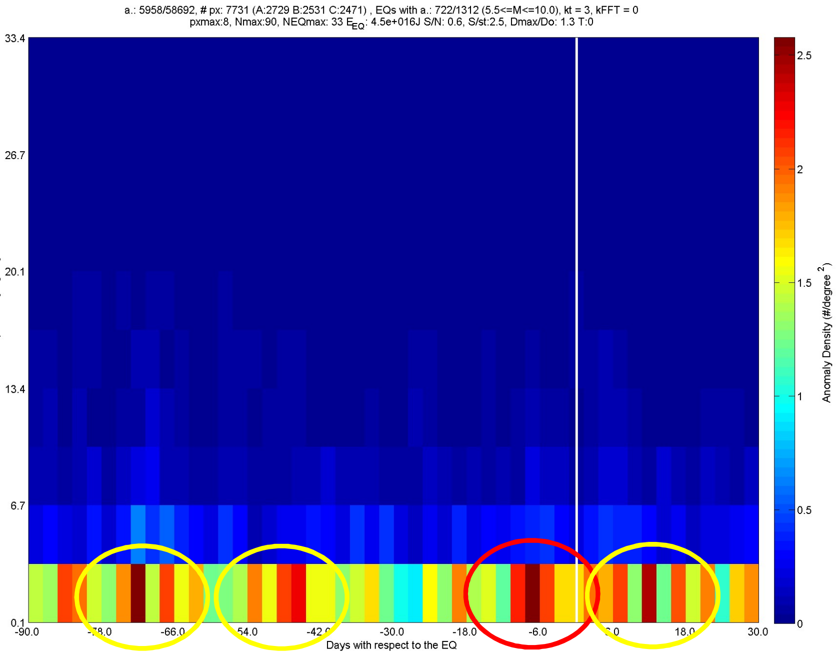
	Anomalies	Anomalies associated with EQs	Anomalies associated with EQs in pMAX	EQs	EQs with anomalies	EQs with anomalies in pMAX
Land	5927 (26.8%)	581 (20.7%)	8 (15.1%)	243 (18.5%)	107 (19.9%)	2 (8.3%)
Sea	16215 (73.2%)	2224 (79.3%)	45 (84.9)%	1069 (81.5%)	431 (80.1%)	22 (91.7%)



Sea EQs are slightly favored

With the Superposed Epoch Approach we notice some concentrations at different times before EQs

Could we explain this with something physical instead of errors?



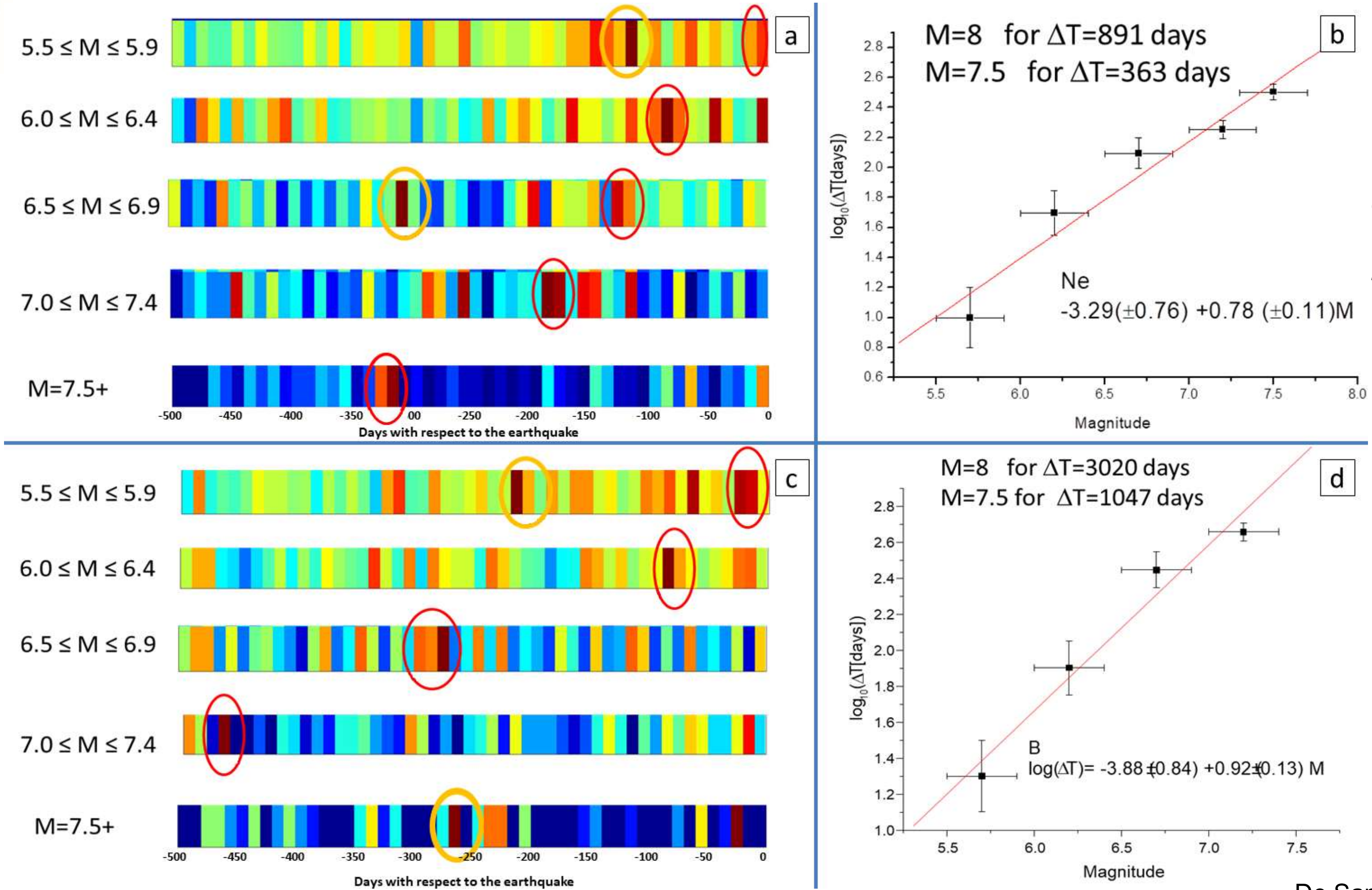
Confirming Rikitake law (1987)

4. Worldwide statistics

Log ΔT(days)=a+bM   *a≈-2 (±1); b ≈0.8 (±0.2)*

Ne

B



a=-3.3 (±0.8);
b=0.8 (±0.1)

a=-3.9 (±0.8);
b=0.9 (±0.1)

De Santis et al., under review

Explaining Rikitake law (1987) as a diffusion process in the lithosphere

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$$\text{Log}\ \Delta T(\text{days}) = a + bM \qquad -a \approx 2\text{-}4;\ b \approx 0.8$$

Adopting a **lithospheric process of stress diffusion** across the Dobrovolsky area, we can write:

$$R_{Db} = \sqrt{4\pi D \Delta T} \qquad (1)$$

where D is the **diffusivity**; **ΔT is the precursor time** if the first precursor appears at the beginning of the stress evolution. R_{Db} is the spatial distance (in km) of the anomaly from the earthquake epicentre, as:

$$log R_{Db} = \beta M \qquad (2)$$

(β=0.43 and *M*=earthquake magnitude).

If we replace eq. (1) R_{Db} in (2), the Rikitake law coefficients become:

$$a = -\log(4\pi D) \quad (3a) \qquad \text{and} \qquad b = 2\beta \quad (3b)$$

From our results we confirm the relationship (3b) and even deduce D from (3a) (putting the intermediate value *a*=-3):

$D \cong 100\ m^2/s$ of the same order of **slow earthquakes** (Ide et al. 2007)

De Santis et al., under review

5. Conclusions/1
Messages to take home

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5. Conclusions

5.1 **LAIC** effects can be detected **by space**
(but with caution and together with ground data observations!)

5.2 **Satellite & Ground** data analysis in SAFE resulted quite successful for 9 out of 12 largest EQs

5.3 Most of the anomalies are really EQ-related **anticipating EQs by few days to about three months, but not all EQs couple with above atmosphere-ionosphere**

5.4 EQs **under the sea** are more favoured than those in land

5. Conclusions/2
Messages to take home

5. Conclusions

5.5 Largest concentrations are **2 times larger** than random simulations, **10-20 times** outside their standard deviations

5.6 We confirm **Rikitake law** and explain it as **a lithospheric diffusion process**

5.7 Warning

- **Statistical correlation anomalies vs. EQs does not mean EQ prediction**: uncertainties about position, time and magnitude are too large.
- **False alarms are many** and mostly due to natural irregular variations of ionosphere. We do not expect to have continuous ionospheric perturbations and the satellite is “above” a seismic area only a few minutes per day.

5.8 More case studies, more satellites and more extended worldwide statistical analyses are needed to confirm our results and to understand which is the best physical model of LAIC

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* Former INGV; ** Now at INGV

SAFE Team + ESA Officers +
ASI representatives & Rapporteurs

SAFE

Swarm for earthquake study

Thanks for your attention !

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Some bibliography by SAFE Team:

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Swarm for earthquake study

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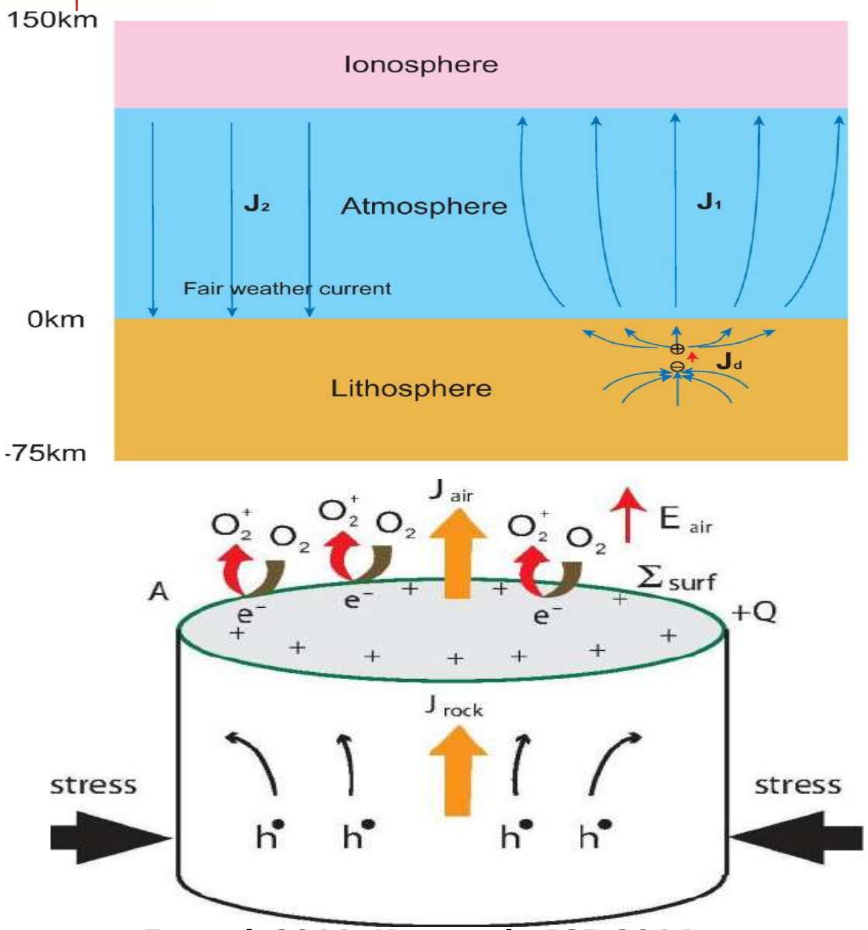
The Physics: LAIC Models

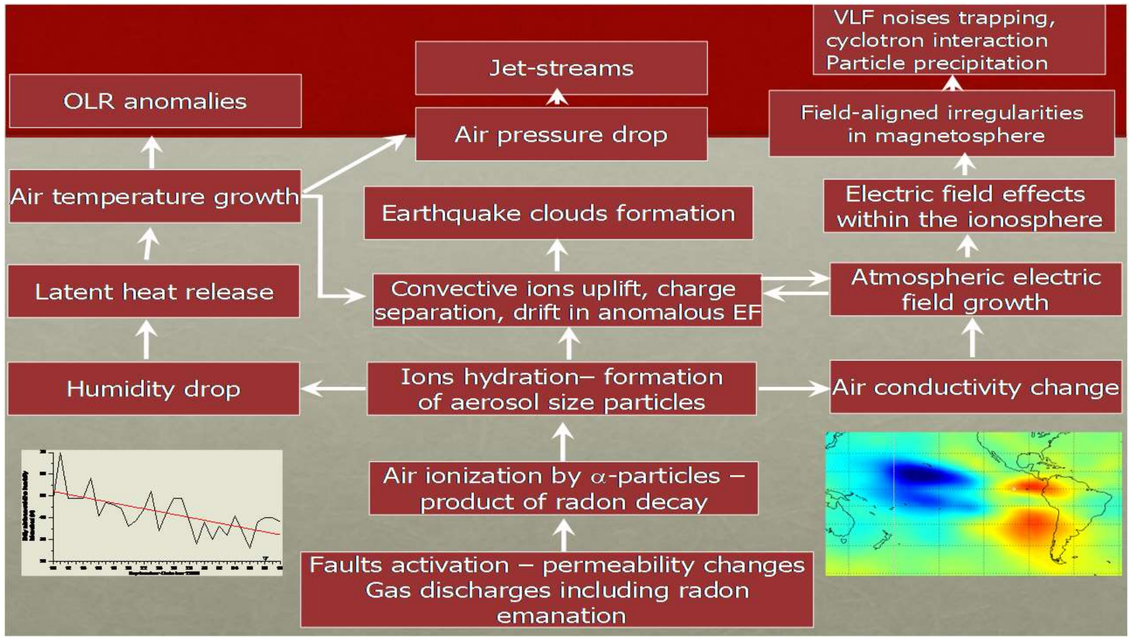
Current Dynamos for LAIC coupling

1. *Dynamo from stressed rocks (Freund, JAES, 2011)*
2. *Dynamo from injection of radon and charged aerosols (Pulinets & Ouzounov, JAES 2011; Sorokin and Hayakawa, MAS 2013)*



Freund, 2011; Kuo et al., JGR 2014

Atmospheric ***Electromagnetic***



Pulinet& Ouzounov, JAES 2011