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Fast acquisition of focal mechanism based on statistical analysis

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European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823844

- The aim of **urgent seismic computing** is to provide ground shaking maps with severe time constraints in order to assist stakeholders in damage assessment.

- Our motivation is to provide a **fast methodology to determine the earthquake focal mechanism** parameters required by **physics-based** seismic wave simulation codes.

- Also, as a part of **uncertainty studies,** we estimate PGV variations as function of the focal mechanism and depth. These variations can contribute to providing more accurate error bounds in simulated PGV maps.

- Physic-based synthetic PGV can help in hazard assessment
- Early CMT solutions might not be available or be unreliable immediately after the EQ's recording.
- Uncertainties in focal mechanism have unknown impact in PGV

- To develop a statistical tool for a fast focal mechanism (FM) estimation based on the regional large, nearby, historical CMT database.

- To quantify the variation on the ground shaking maps considering different FM and depth values using the AWP-ODC seismic modeling code.

- The historical CMT datasets are queried at the Global Centroid Moment Tensor Project (Dziewonski et al., 1981; Ekström et al., 2012). As test cases, we select these five different seismo-tectonic regions: Japan, New Zealand, California, Iceland, and Italy.

Region	Latitude [°] (min. \ max.)	Longitude [°] (min., max.)	Depth max. [km]	Number of events	Magnitude (min. \ max.)	Years period
New Zealand	-46.0 \ -34.4	166.1 \ 178.71	518	273	4.8 \ 7.8	1965-2018
Japan	30.0 \ 46.3	128.84 \ 147.1	588	2652	4.6 \ 9.1	1967-2019
California	29.7 \ 44.8	-129.8 \ -110.4	30	460	4.4 \ 7.3	2010-2019
Iceland	63.0 \ 66.9	-24.4 \ -16.6	33	124	4.6 \ 6.5	1976-2018
Italy	34.9 \ 47.9	5.2 \ 21.0	502	692	3.9 \ 6.9	1976-2015

Table 1. Basic information from https://ds.iris.edu/spud/momenttensor

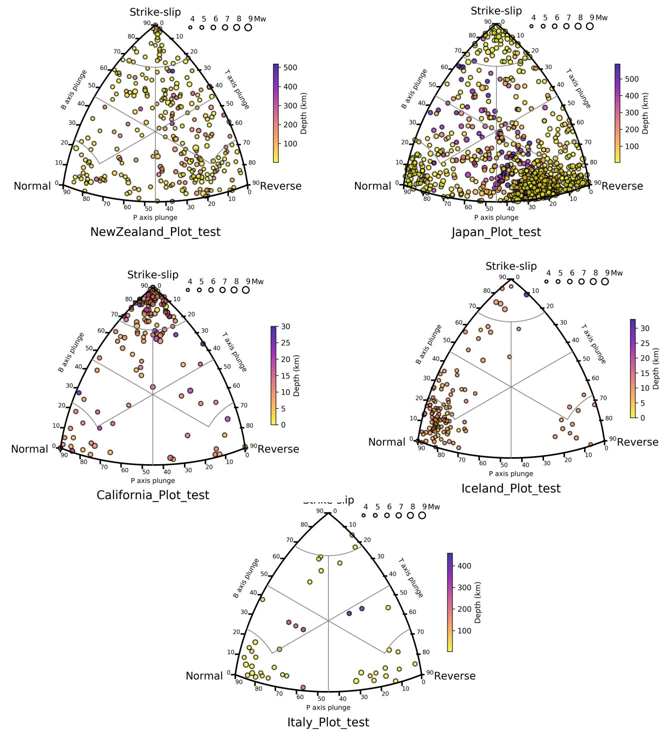


Fig. 1 Focal mechanisms represented in Kaverina diagrams, (a) New Zealand M ≥ 4.8, (b) Japan M ≥ 5.5, (c) California M ≥ 4.4, (d) Iceland M ≥ 4.6 (e) Italy M ≥ 4.6 (Kaverina et al., 1996., Alvarez-Gomez, 2019)

1. We split these datasets into **training** and **test** sets. The test set consists of only one event that acts as the newly registered earthquake (light blue beachball in Fig 2). The test event is randomly selected from the dataset. The training set collects all remaining events in the dataset.

2. We apply the k-nearest neighbor algorithm to identify closest events to the test event in a given radius $d_{th.}$ The maximum number of neighbors allowed inside the sphere is k_{max}. Moreover, we quantify the minimum number of neighbor events, $k_{min,}$ that optimizes the results of this methodology. M_{th} is threshold magnitude, such all events larger or equal than M_{th} is considered in the analysis.

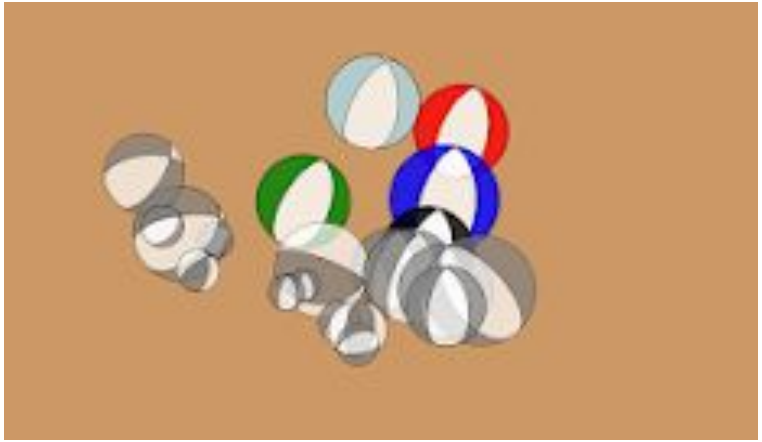


Fig. 2 Example of the spatial distribution of twenty FM in a sphere of d_{th} = 50 km radius. The test event is the light blue beach ball. The four nearest neighbors are depicted in red k=1, green k=2, blue k=3, and black k=4 color. The Beachball size is relative the event magnitude.

3. We compute a hypothetical FM using the median values of strike, dip, rake, considering all neighbors inside d_{th}. We also select the four nearest neighbors to the test event, named k=1, k=2, k=3, and k=4.

4. The similitude of two different FMs is quantified by the Minimum Rotated Angle (MRA) proposed by Kagan (2007). We compute the MRA per each of the five selected neighbors to our test-event.

5. A parametric analysis (d_{th}, k_{max}, k_{min}, M_{th}) is done at each of the five testing regions. We look for the set of parameters that increases the similarity between FMs, i.e., reduces the MRA values.

6. Steps 1 to 5 are repeated until the total dataset length is reached.

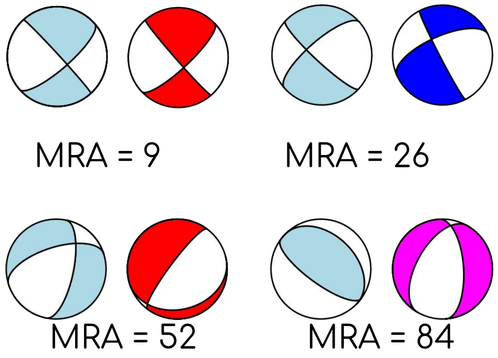


Fig. 3 Example of the MRAs computed for the tested earthquake (light blue beach ball), and the most similars training neighbors. The color of the beachball indicates spatial proximity, where the nearest neighbor k=1 is shown in red color, k=2 in green color, k=3 in blue, k=4 black color, or the hypothetical in magenta color.

Kagan, Y. Y. (2007). Simplified algorithms for calculating double-couple rotation. *Geophysical Journal International*, *171*(1), 411-418.
Kaverina, A. N., Lander, A. V., & Prozorov, A. G. (1996). Global creepex distribution and its relation to earthquake-source geometry and tectonic origin. *Geophysical Journal International*, *125*(1), 249-265.
Álvarez-Gómez, J. A. (2019). FMC—Earthquake focal mechanisms data management, cluster and classification. *SoftwareX*, *9*, 299-307.

1. We consider an MRA threshold to identify the most similar focal mechanisms. After a subjective analysis, we adopt a value of MRA ≤ 30 to consider "similar" FM.

2. We search for an optimal parameter combination of d_{th}, k_{min}, and M_{th} such that increases the number of events with MRA ≤ 30. Before the analysis we select the events with magnitude larger than M_{th}

First, to find the optimal radius of the sphere d_{th}, we fix the minimum number of neighbors that must be inside the sphere, k_{min}= 1. The maximum number of neighbors remains constant, k_{max} = 20. We choose a d_{th} value such that maximizes:

a) the number of events in the analysis (red markers in Fig 4),
b) the percentage of MRA ≤ 30 (blue markers in Fig. 4).

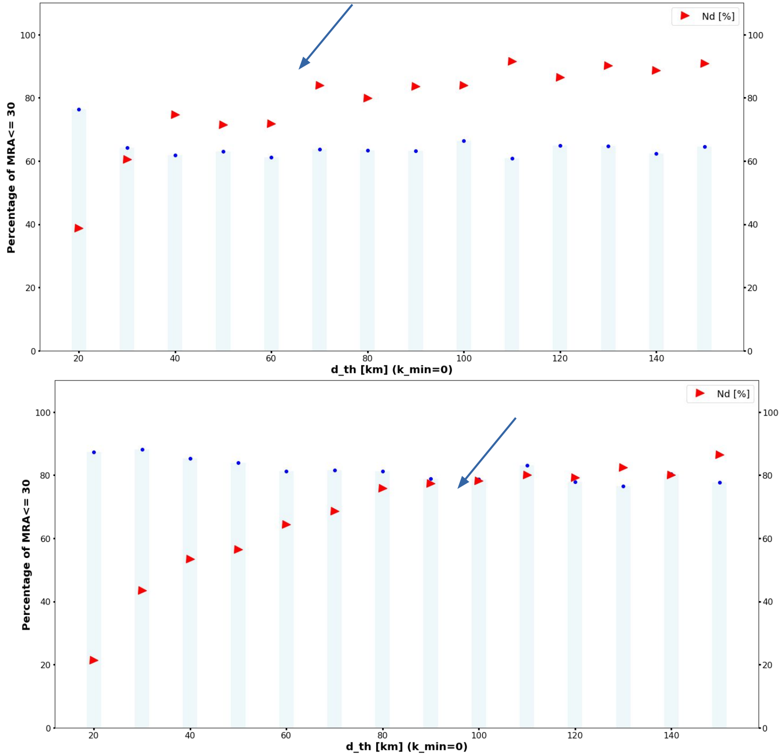


Fig. 4 Results of the optimum d_{th} parameter considering k_{min}= 1. The Upper figure shows the results for New Zealand region, and lower for Japan. . Blue markers are the percentage of values with MRA ≤ 30. Red markers are the percentage of data used in the analysis

3. Once d_{th} is fixed we similarly search the optimum k_{min}. We select the k_{min} that:

a) increases the number of events in the analysis (Fig. 5 red markers),
b) with a high percentage of MRA ≤ 30 (blue markers).

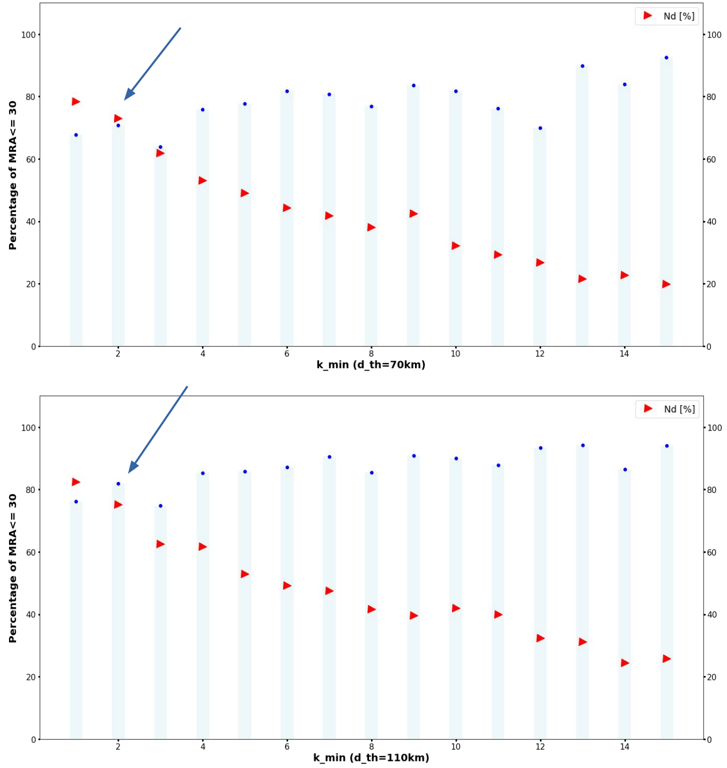


Fig. 5 Results in finding the optimum dth parameter considering kmin=1. The Upper figure shows the results for New Zealand region, and lower for Japan. .

4. Once d_{th} and k_{min} are selected we statistically analyze the behavior of the MRA' for the neighbors k=1, k=2, k=3, k=4, k_{median}. We find the minimum of the five MRA computed (for k=1, k=2, k=3, k=4, and k_{mean}) per each test event (Fig. 6).

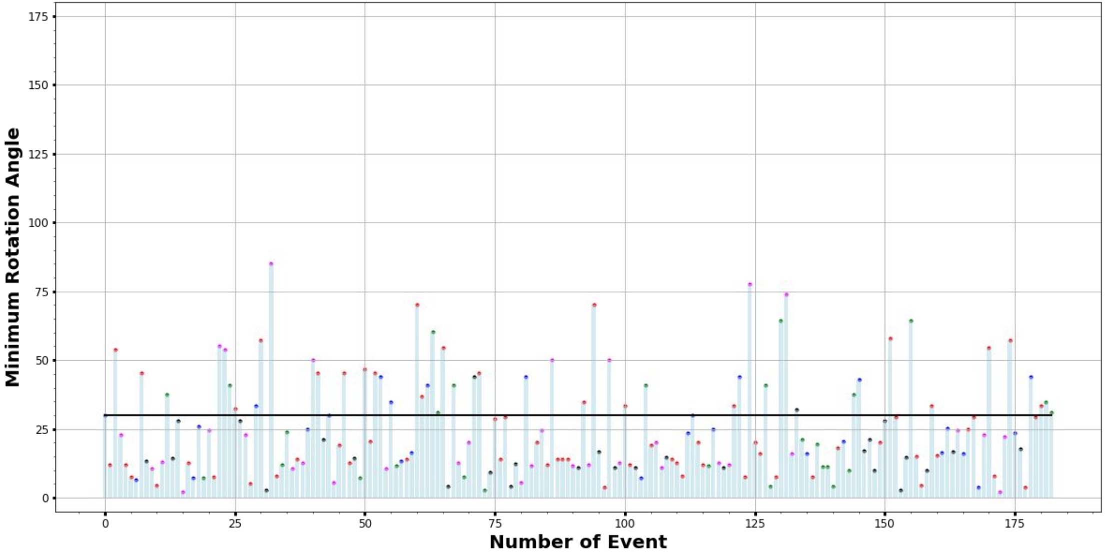


Fig. 6 Statistical analysis of the minimum value find in the MRA of k=1, 2,3 ,4 and k_{median}., for New Zealand region.

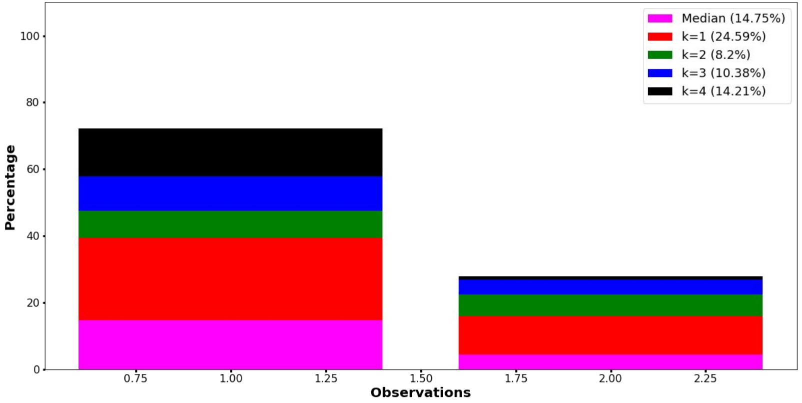


Fig. 7 Contribution of each neighbor to minimizes the MRA.

RESULTS

Region	k_{max}	k_{min}	d_{th} [km]	M_{th}	Total num.ev.	Nb[%].	MRA ≤ 30 [%]
New Zealand	20	2	70	4.8	273	73 %	77.7 %
Japan	20	2	110	6.0	331	80 %	80.2 %
California	20	2	50	5.5	153	80.5 %	78.8 %
Iceland	20	1	100	5.0	83	100 %	80.2%
Italy	20	1	100	4.8	118	80.5%	80 %

Table 2 Statistical results of the similarity methodology. Nb is the percentage of events that fulfill the conditions of dth, Mth, kmin. MRA indicates the percentage of Nb elements within MRA ≤ 30

IMPACT

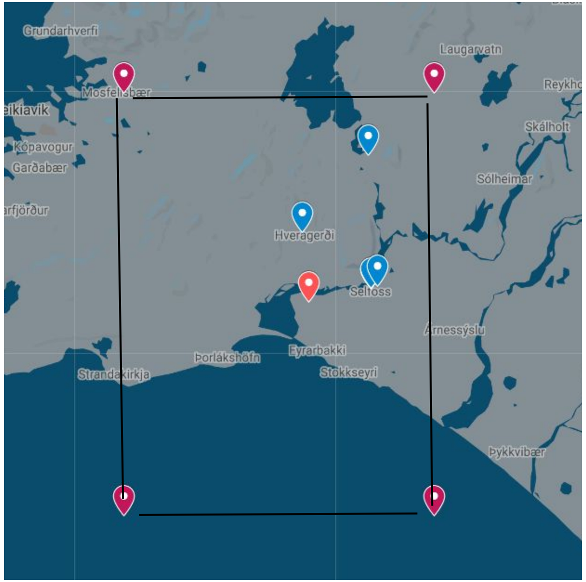
1. Quantify the sensitivity of MRA perturbations on synthetic PGV.

2. We simulate seismograms using point sources in the Anelastic Wave Propagation FD code by Olsen, Day and Cui (AWP-ODC: http://hpgeoc.sdsc.edu/AWPODC/)

3. As reference case, we use the 29/05/2008 Mw = 6.3 Iceland doublet earthquake

Iceland doublet earthquake 29/05/2008

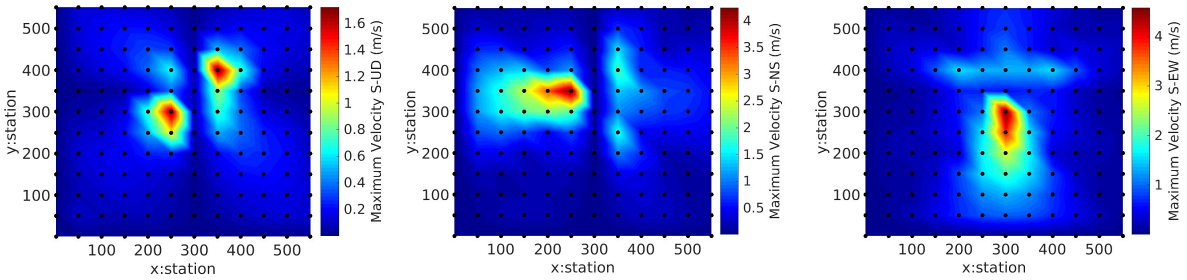
Point source (Decriem et al., 2010)	
Strike	0º
Dip	90º
Rake	180º
Mw	6.3
Mo	$3.38\ 10^{18}$
latitude	63.96º
longitude	-21.06º
depth	5.447 km



Modeling region at the Southern Iceland Seismic Zone (SISZ)	
min long	-21.6667
max long	-20.833
min lat	63.6667
max lat	64.1667

Evaluation Methodology

1. Peak Ground Velocity (PGV) maps with different initial FM are simulated. At each synthetic station, we compute the maximum value of the velocity traces $Vel\_Train(n)_i$, for the three components, i = EW, SN, UD.

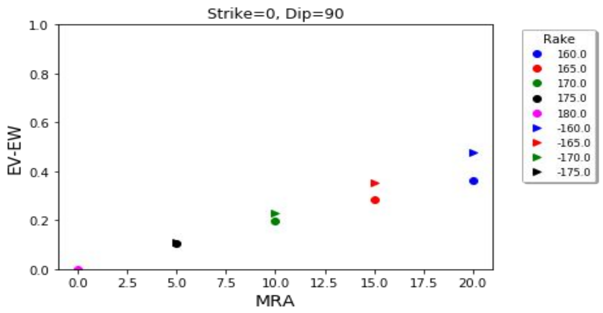


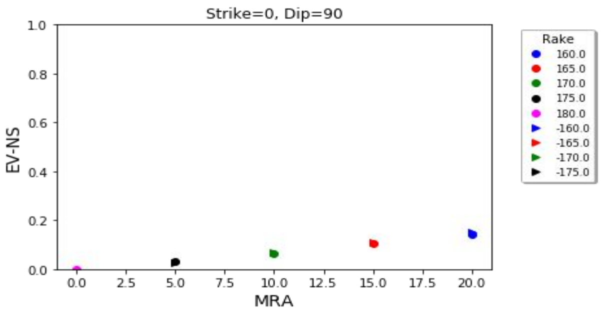
2. Our reference PGV map, $Vel\_Ref(n)_i$ has a pure strike-slip FM: [0,90,180]. Then all subsequent PGV maps are for different FM, $Vel\_Trail(n)_i$. Hence, an **absolute difference computed for each map** is obtained as:

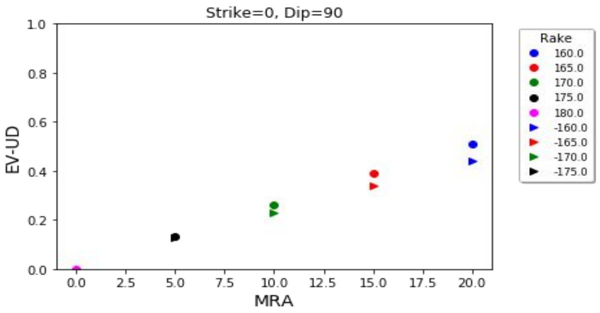
$$EV_i = \max(\mathrm{abs}(Vel\_Trail(n)_i - Vel\_Ref(n)_i)) / \max(\mathrm{abs}(Vel\_Ref(n)_i)$$

Evaluation Results

Strike = 0, Dip = 90 (only varying the rake)







- As the MRA increases (i.e. the rake increases,), velocity variations EV linearly increases in the three components.
- The EW (east-west) and UD (up-down) velocity components show a larger slope than the NS component.
- The maximum variation EW is found for a the rake = 160° and -160°, with an error ~ **40%**.
- The maximum variation for NS (north-south) component is ~ **15 %** for a rake = 160° and -160.
- The maximum variation in UD component is ~**45%** for rake = 160° and -160°.

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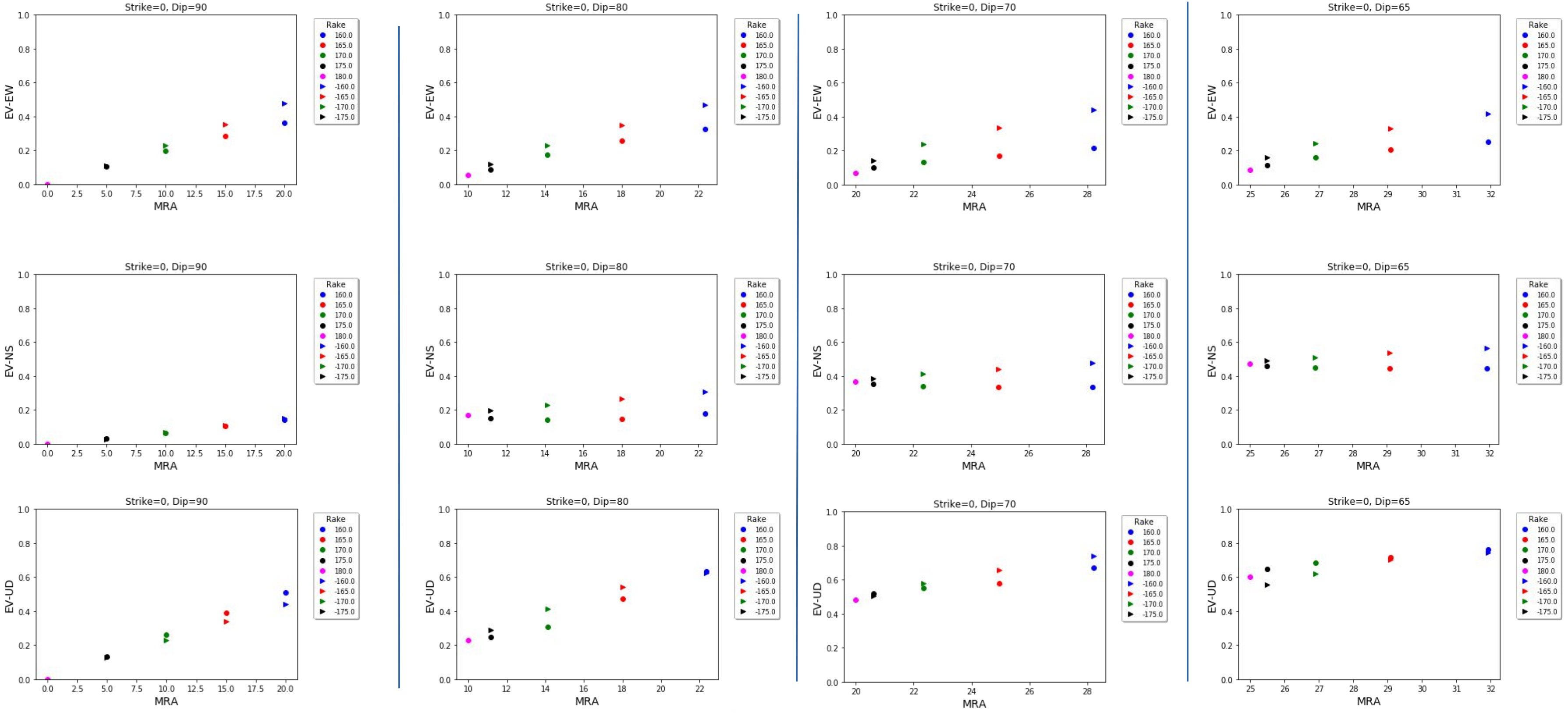
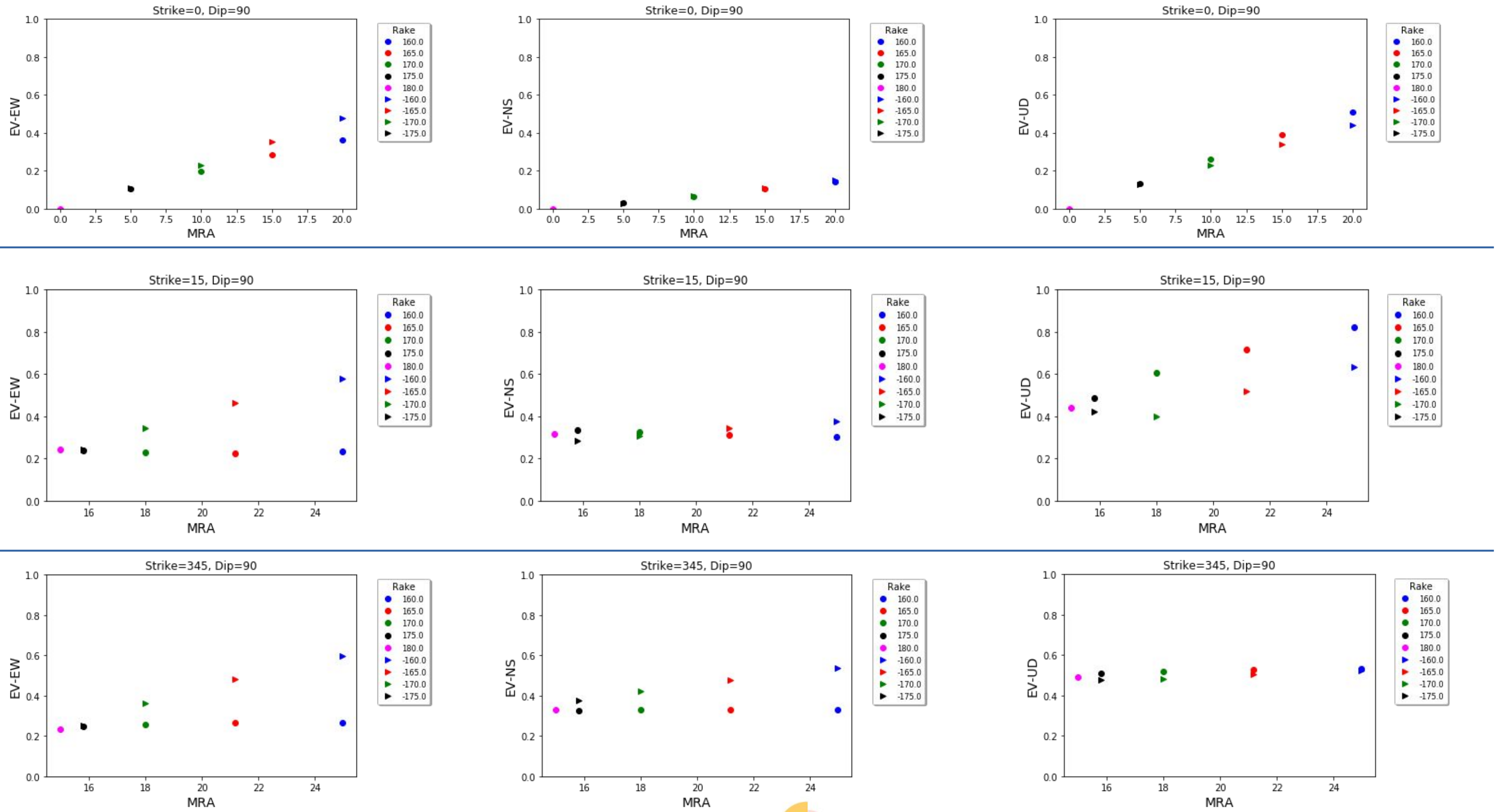
Strike = 0, Dip = [90,80,70,65], Rake = [180 , 175, 170, 165, 160, -160, -165, -170, -175]

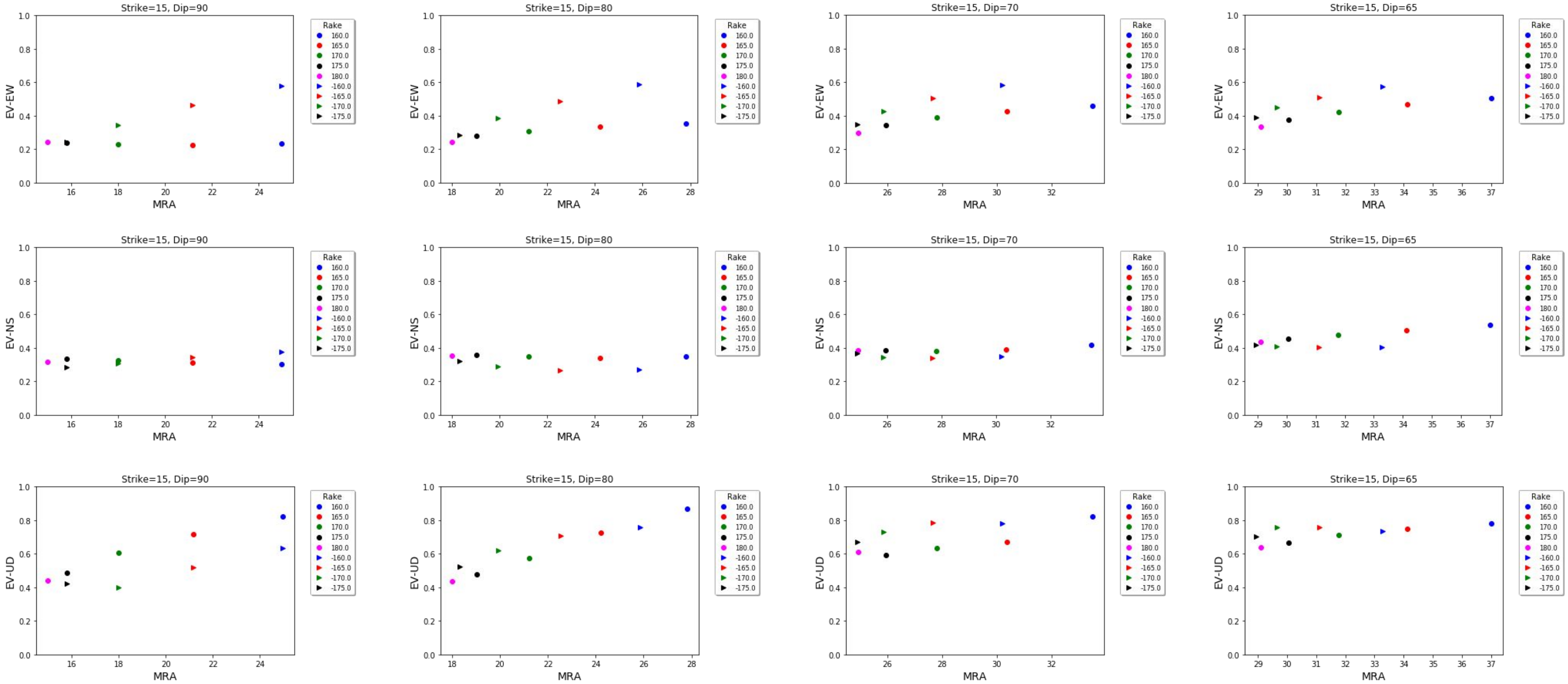


- Is worth to note the **almost linear relations between MRA and EVi'**
- A difference of EVi when the rake direction changes from negative to positive appears for NS and EW components
- In the case of EW velocity component, the variation is similar for different Dip values. This component is more correlated with the rake variation. The negative rake direction increases the difference in the EW component.
- The NS variation is highly dependent on the Dip variation, and less dependent on rake variation. The negative rake direction shows a higher slope than positive values.
- The variation in the UD component is the highest of the three components. It depends on both the rake and dip values. For a variation in the dip of 20°, the difference increases from ~0% to ~40% for the rake=180°. In this case the rake direction is not relevant to compute the variation of the PGV in the UD component.

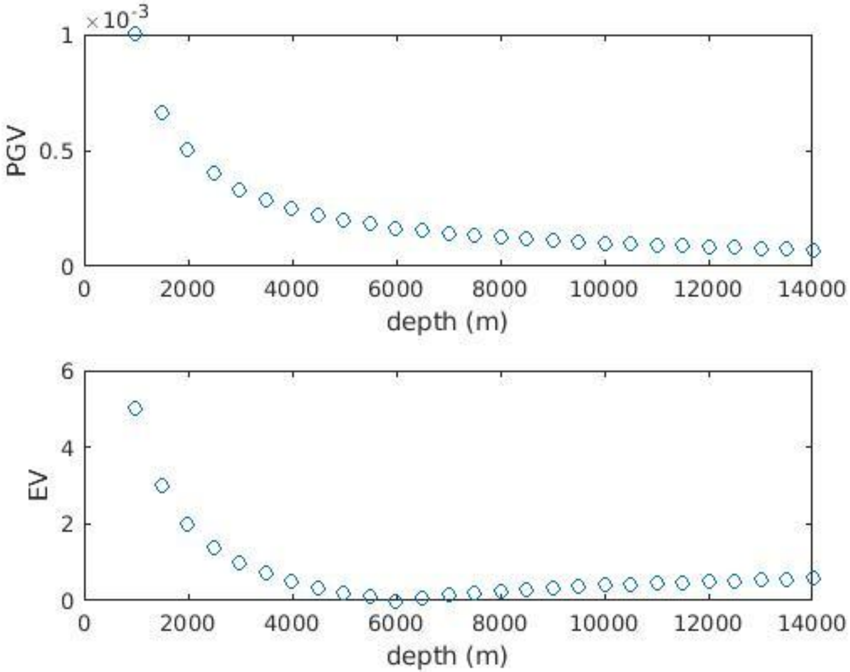
Strike = 0° *vs* 15° and 345°



Strike = 15°


Strike=15, Dip=90
Strike=15, Dip=80
Strike=15, Dip=70
Strike=15, Dip=65
EV-EW
EV-NS
EV-UD
MRA
Rake
160.0
165.0
170.0
175.0
180.0
-160.0
-165.0
-170.0
-175.0

Depth sensibility analysis

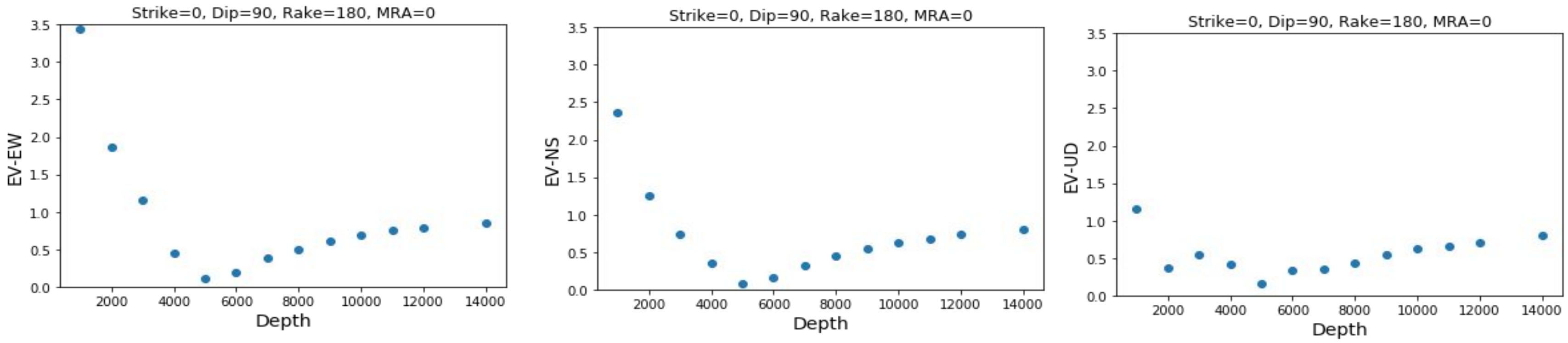


Amplitudes decay with the inverse of the distance for homogeneous media, albeit our EV metric would display a kink because it compares PGV with that at a reference depth.

Theoretical values:

Amplitude α 1/depth

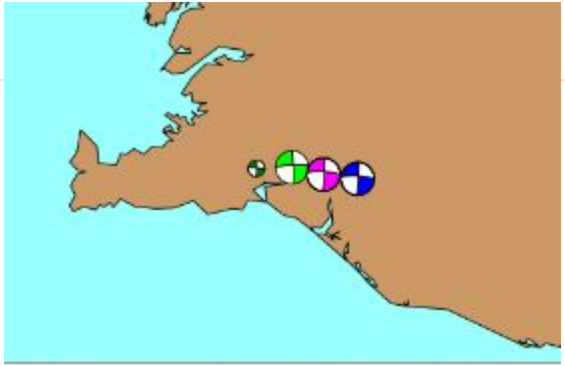
Depth sensibility analysis



The depth shows a similar pattern that the theoric in the variation on the PGV measure. The observed differences could be related with the velocity model. The lower EVi corresponds to a depth close to the real earthquake depth we are comparing with. From this lower point as the depth decreases the EVi becomes larger with a deeper slope than for larger depth. It is important to consider these variations to provide accurate uncertainty over the PGV maps.

Study case: Iceland doublet earthquake 29/05/2008

	"New event" (light green)	k=1 (magenta)	k = 2 (dark green)	k= 3 (blue)
Strike	267°	2	274	4
Dip	78°	85	86	86
Rake	-7°	-167	-5	-164
MRA	----	4.47	11.70	7.60



Global CMT location	
longitude	-21.17
latitide	63.92
depth	12000 m
Hipocenter Located in the domain	X: 246 Y: 283 Z: 121
Magnitude	6.3
Moment	3.38e+18

Study case: Iceland doublet earthquake 29/05/2008

COMPONENT	EV (k-neighbor=1)	EV (k-neighbor=2)	EV (k-neighbor=3)
NS	0.15	0.29	0.24
EW	0.13	0.42	0.20
UD	0.12	0.27	0.22
MRA	4.47	11.70	7.60

Open questions

- How would EVi vary with simultaneous uncertainties in-depth and CMT.
- How can we consider MRA and depth uncertainties for further computing stages?
- How would these results vary for a realistic 3-D velocity model?
- How would these results effectively impact on the hazard curves?

- We propose using fast (<20 s) CMT estimates from a stochastic method. In particular, we assign the FM of a close (large) historical earthquake to a new event.
- MRA is used as a similarity metric for two FMs.
- We find optimal parameters for FM estimation (minimum number of neighbors k_{min}, neighborhood radius d_{th}, and threshold magnitude M_{th}).
- Our algorithm finds suitable FM values (MRA <= 30) in 80% of cases, for five studied regions.
- We can bound maximum PGV errors as function of MRA, as they both are linearly related.
- Depth variations have simpler impact in PGV, at least with 1D velocity models and flat topography. Combined dependence between depth and FM for complex models is ongoing work

In the context of urgent seismic simulations, we can obtain fast FM estimates and assess maximum/minimum PGV variation due to location/mechanism uncertainties.

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Thank you

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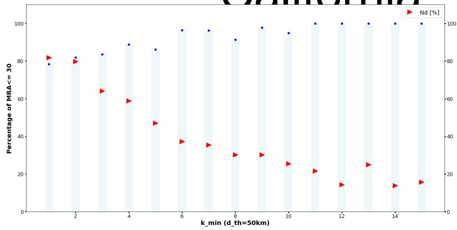
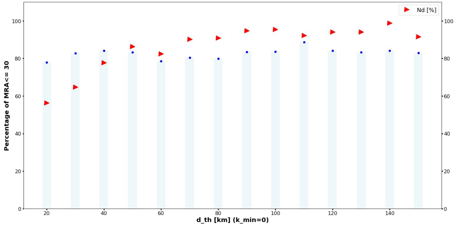
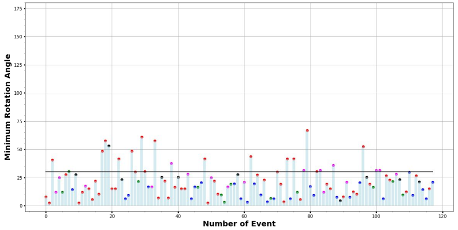
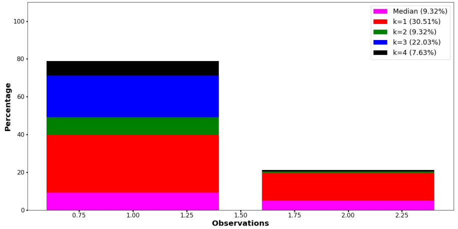
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823844

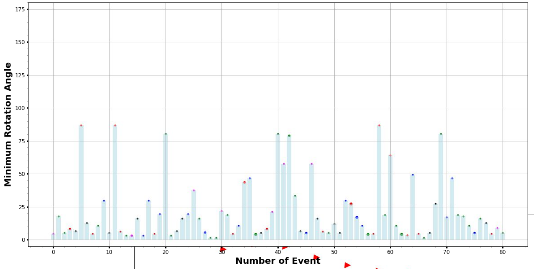
California

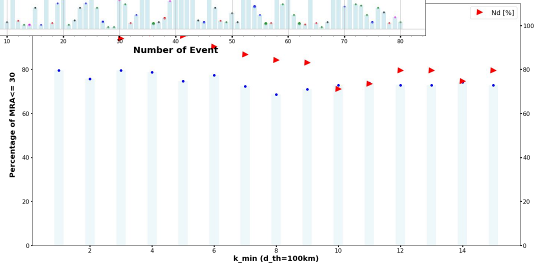

Nd [%]
Percentage of MRA<= 30
k_min (d_th=50km)

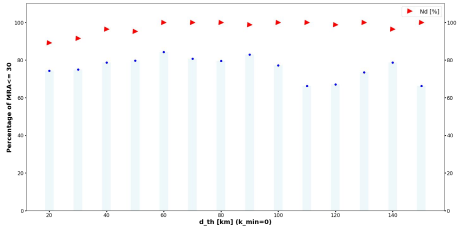

Nd [%]
Percentage of MRA<= 30
d_th [km] (k_min=0)

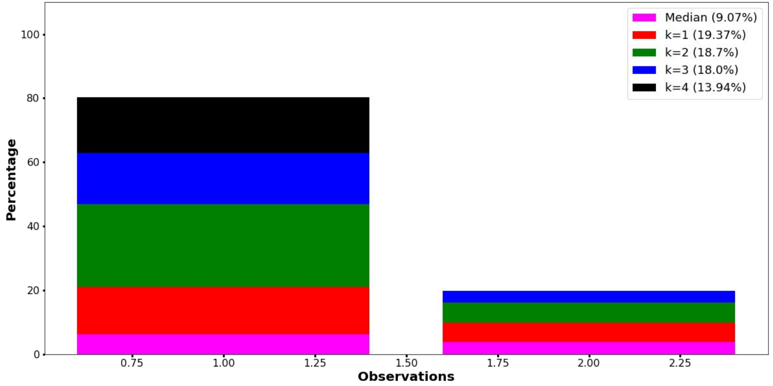

Minimum Rotation Angle
Number of Event


Median (9.32%)
k=1 (30.51%)
k=2 (9.32%)
k=3 (22.03%)
k=4 (7.63%)
Percentage
Observations

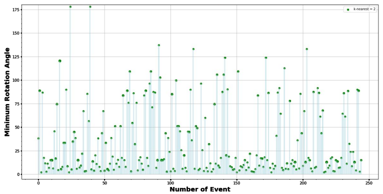

Minimum Rotation Angle
Number of Event

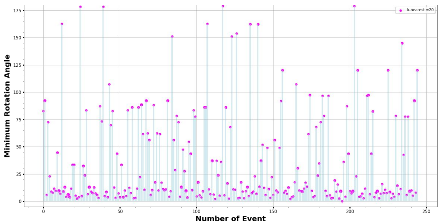

Nd [%]
Percentage of MRA<= 30
k_min (d_th=100km)

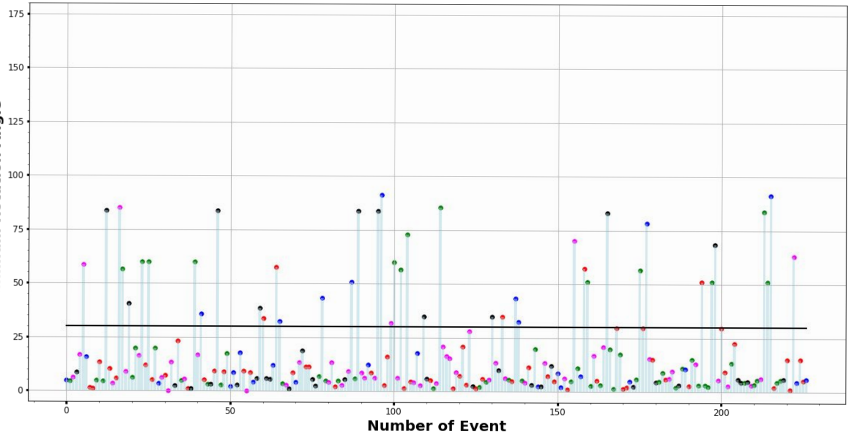

Nd [%]
Percentage of MRA<= 30
d_th [km] (k_min=0)

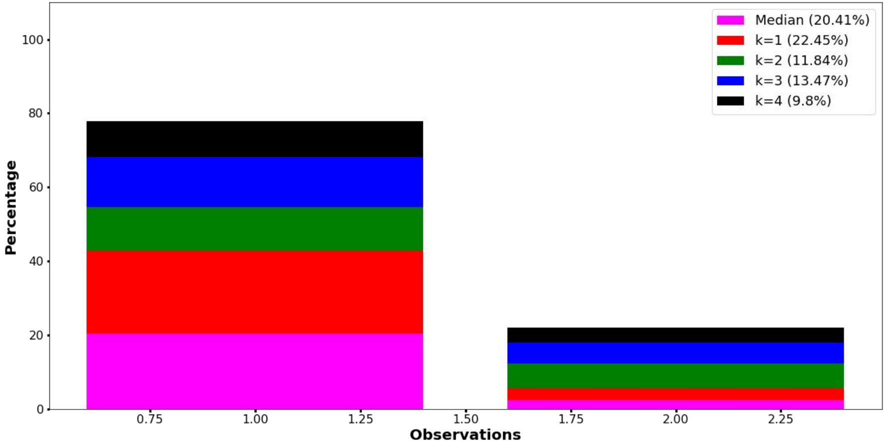

Median (9.07%)
k=1 (19.37%)
k=2 (18.7%)
k=3 (18.0%)
k=4 (13.94%)
Percentage
Observations

Japan

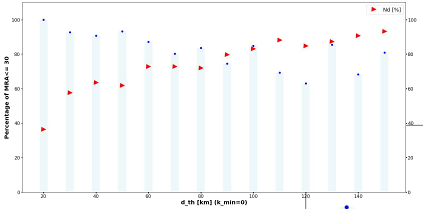

Minimum Rotation Angle
Number of Event

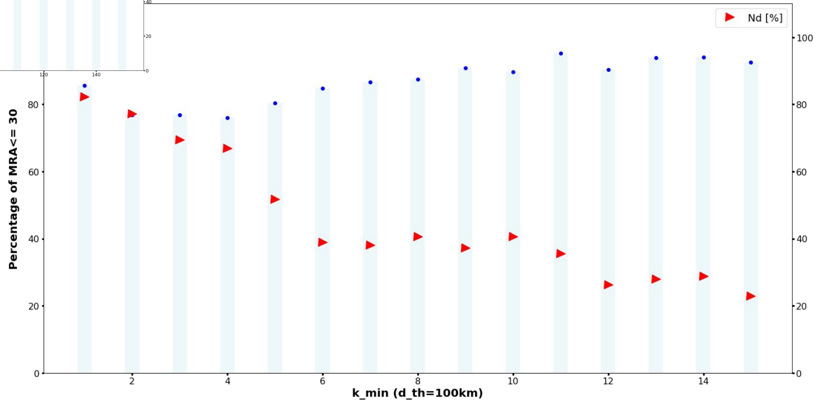

Minimum Rotation Angle
Number of Event

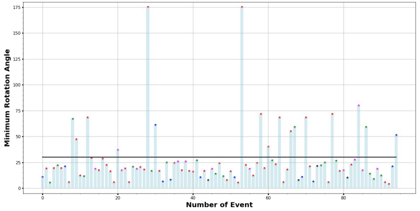

Number of Event

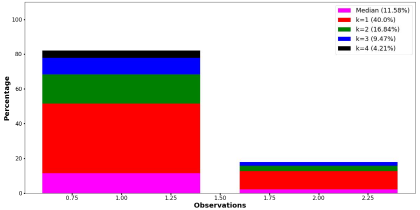

Median (20.41%)
k=1 (22.45%)
k=2 (11.84%)
k=3 (13.47%)
k=4 (9.8%)
Percentage
Observations

Italy


Nd [%]
Percentage of MRA<= 30
d_th [km] (k_min=0)


Nd [%]
Percentage of MRA<= 30
k_min (d_th=100km)


Minimum Rotation Angle
Number of Event


Median (11.58%)
k=1 (40.0%)
k=2 (16.84%)
k=3 (9.47%)
k=4 (4.21%)
Percentage
Observations