



CTBTO
PREPARATORY COMMISSION

COMPREHENSIVE
NUCLEAR-TEST-BAN
TREATY ORGANIZATION

Efforts toward automatic aftershock sequences processing at the IDC

Christos Saragiotis

CTBTO, IDC/SA/SM

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Overview of the IMS network and IDC pipeline

The project

Experiment constraints

Detection statistics

Event statistics

Bulletin comparison

Analyst workload

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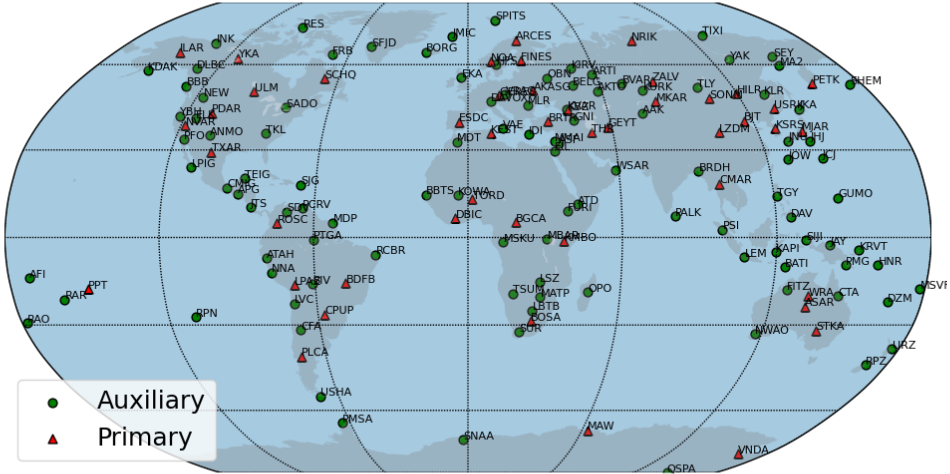
Detection statistics

Event statistics

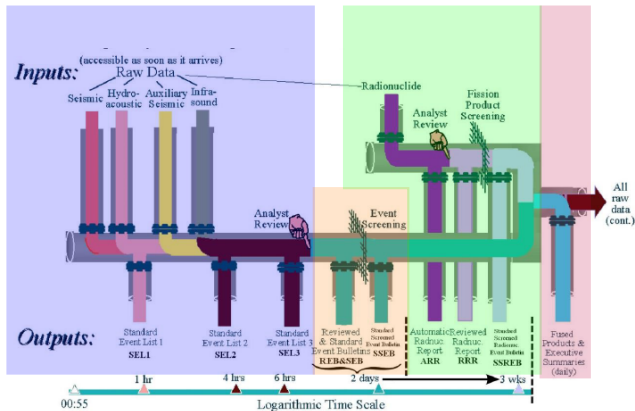
Bulletin comparison

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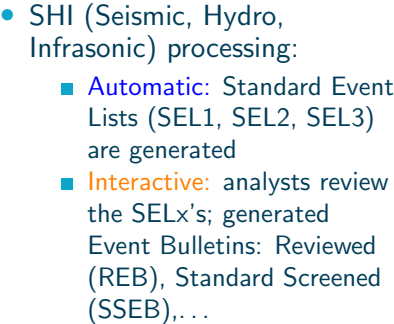
The IMS seismic network



The IDC processing pipeline



- SHI (Seismic, Hydro, Infrasonic) processing:
 - Automatic processing
 - Interactive processing
- Radionuclide processing
- Technology fusion



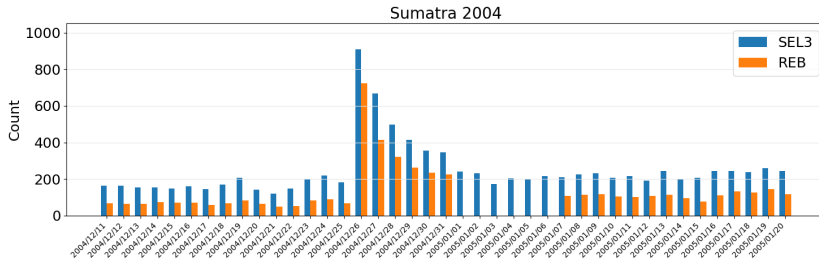
The IDC processing pipeline

- **Automatic stage:** is completed within 6 hours from event time.
- **Interactive stage:**
 - IDC analysts review the events of the SEL3 and may split, merge, delete or create new events, re-pick phases or pick new ones among other things
 - is very time-consuming and work intensive.
 - is to be completed within 2 days from event end of day.
- All three methods generate detection lists as well as event lists, they are therefore independent generators of a SEL3-type lists.

Large events with numerous aftershocks

- increase the no. of events by an order of magnitude
- deteriorate the quality of the automatic event lists
- increase the work of analysts
- have impact on *associated phases* and *added events* rates metrics

Motivation



- Seismic activity during that period was so intense that it was impossible for interactive processing to keep up with the volume of events.
- Eventually the IDC had to give up processing of this time period in order to catch up with the current event processing. This is why there is a gap of 6 days in the REB.
- More than 1000 events were processed from July until December 2005, i.e. at least six months later.

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Support of the EU to the PTS

The European Commission supported PTS activities including this project (CFSP 2018/298).

Objectives: *“to prototype and compare the performance of up to three approaches at improving the processing of aftershock sequences. Algorithms under consideration are:*

- *two cross-correlation approaches*
- *an approach based on AR-AIC methods.”*

In particular,

EMF: Based on matched filtering, grid search and association using a characteristic function;

SeisCorr: Based on cross-correlation with templates; single- and multi- station validation modes;

XSEL: Based on cross-correlation with templates; features local association and conflict resolution stages.

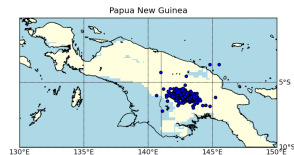
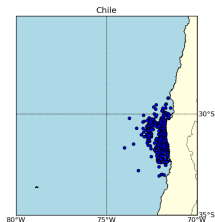
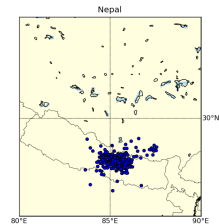
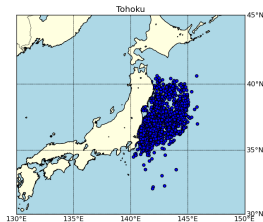
- Developed at NORSAR;
- Based on matched filtering, grid search and association using a characteristic function;
- Iterative detection and phase association;
- Single station pipeline → regional pipeline → global pipeline;
- Provides partial events.

- Developed at Sandia National Labs;
- Based on cross-correlation with templates (historic waveforms);
- Validation modes:
 - single-station;
 - multi-station.
- Provides partial events.

- Developed at the IDC;
- Based on cross-correlation with templates (historic waveforms);
- Stages:
 1. Cross-correlation/detection;
 2. Local association: associates phases given a template;
 3. Conflict resolution: selects optimal template;
- Provides partial events.

Aftershock case studies

Location	Date	M_w
Tohoku	Mar 2011	9.1
Nepal	Apr 2015	7.8
Chile	Sep 2015	8.3
Papua, New Guinea	Feb 2018	7.5



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Event definition criteria (EDC) for SEL

In the IDC automatic processing, an event is defined if the sum of the associated arrival defining attributes exceeds a threshold. For SEL the condition is:

$$\sum \text{weights} \geq 3.55$$

Phase type	Station type	Arrival time	Az	Slo
primary seismic	seismic array	1.0	0.4	0.4
secondary seismic	seismic array	0.7	0.4	0.4
primary seismic	seismic 3-C	1.0	0.2	0.2
secondary seismic	seismic 3-C	0.7	—	—
H	hydroacoustic	1.2	0.6	—
I	infrasonic	1.0	0.4	0.4

Phase type	Station type	Onset time	Az	Slo
P-type primary	array	1.0	0.4	0.4
P-type secondary	array	0.4	—	—
S-type regional	array	0.7	0.4	0.4
S-type teleseismic	array	0.7	—	—
P-type	3-C	1.0	0.2	0.2
P-type secondary	3-C	0.4	—	—
S-type regional	3-C	0.7	—	—
S-type teleseismic	3-C	0.7	—	—
H-type	hydro	1.54	—	—
I-type	infra	0.8	1.0	

Condition:

$$\sum \text{weights} \geq 4.6$$

Causality: Only available templates at the time can be used.

Causality is violated if the template event is:

- an REB event that occurred more recently than -3 days before the event day.
- a SEL3 event that is less than 6 hours older than the time interval processed.

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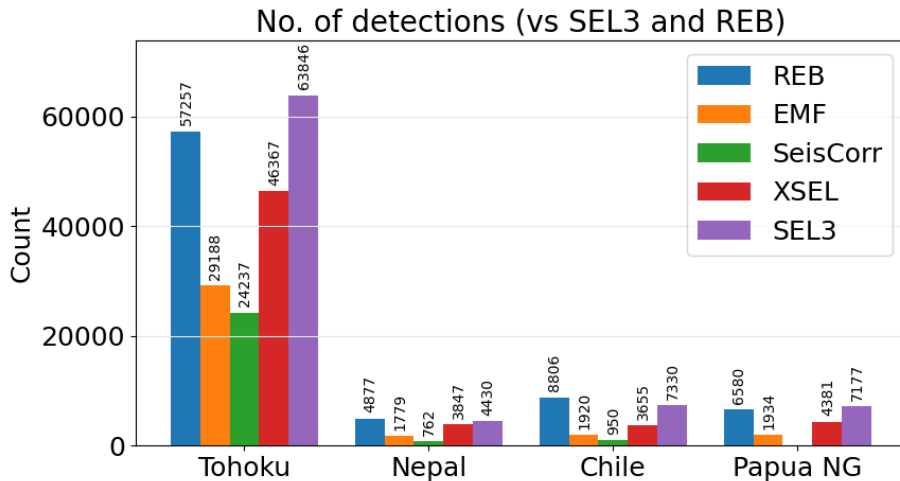
Detection statistics

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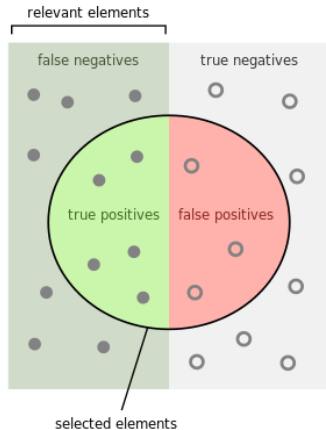
No. of detections



- SEL3 has about 10% more detections than REB (except for the Chile sequence)
- XSEL detects the most arrivals by far
- SeisCorr has few or none detections on the first day, because it uses the events of the first 6 hours as templates
- SeisCorr was not tested on the Papua New Guinea sequence



Recall and precision metrics



How many selected items are relevant?

$$\text{Precision} = \frac{\text{true positives}}{\text{true positives} + \text{false positives}}$$

How many relevant items are selected?

$$\text{Recall} = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}}$$

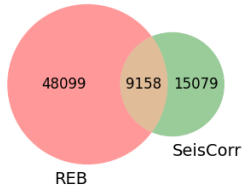
(Source: Wikipedia)

Performance (detections) — Tohoku

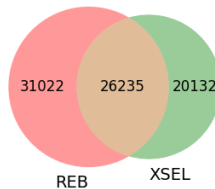
Recall: 0.37
Precision: 0.73



Recall: 0.16
Precision: 0.38



Recall: 0.46
Precision: 0.57



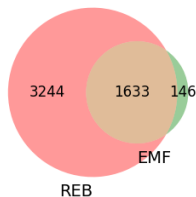
Recall: 0.43
Precision: 0.39



Missed by method Matched by method "False" or unassociated detections

Performance (detections) — Nepal

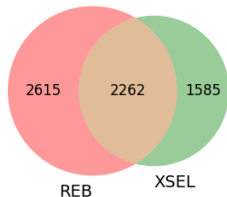
Recall: 0.33
Precision: 0.92



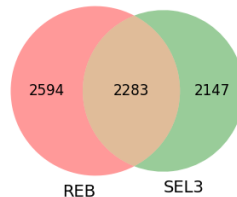
Recall: 0.09
Precision: 0.54



Recall: 0.46
Precision: 0.59



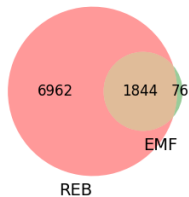
Recall: 0.47
Precision: 0.52



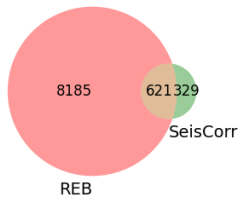
Missed by method Matched by method "False" or unassociated detections

Performance (detections) — Chile

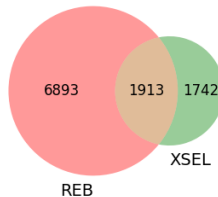
Recall: 0.21
Precision: 0.96



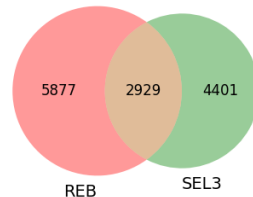
Recall: 0.07
Precision: 0.65



Recall: 0.22
Precision: 0.52



Recall: 0.33
Precision: 0.40



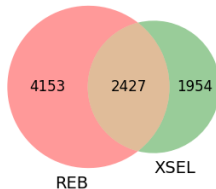
Missed by method Matched by method "False" or unassociated detections

Performance (detections) — Papua NG

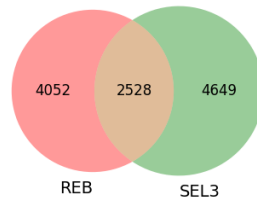
Recall: 0.25
Precision: 0.84



Recall: 0.37
Precision: 0.55

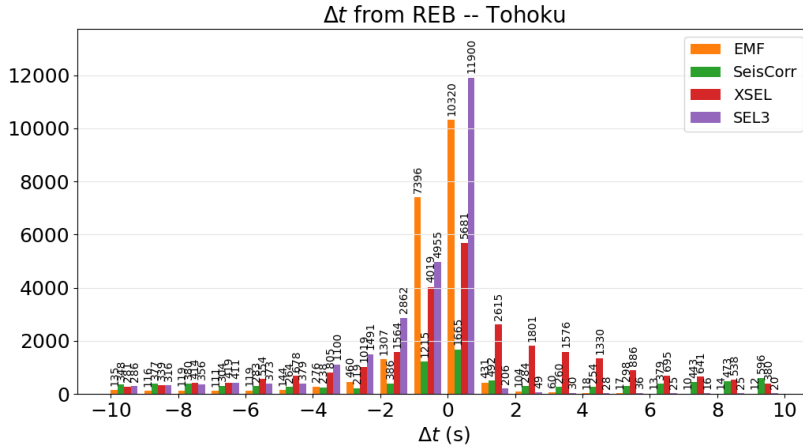


Recall: 0.38
Precision: 0.35



Missed by method Matched by method "False" or unassociated detections

Arrival times compared to REB



(Similar graphs for the other sequences)

Assuming REB is the ground truth. . .

- EMF has the highest precision (least false detections)
- XSEL has the highest recall (highest hit rate)
- SEL3 has balanced precision and recall
- SeisCorr has small recall (but uses less stations)
- No significant bias of arrival times for all methods

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Detection statistics

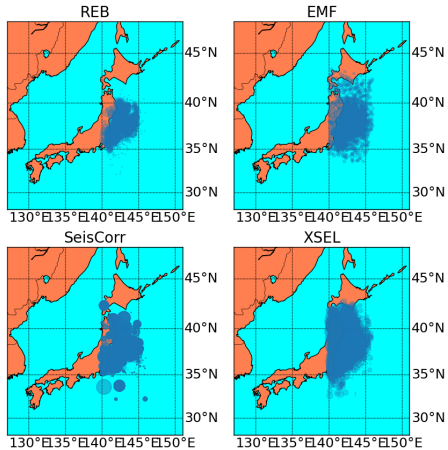
Event statistics

Bulletin comparison

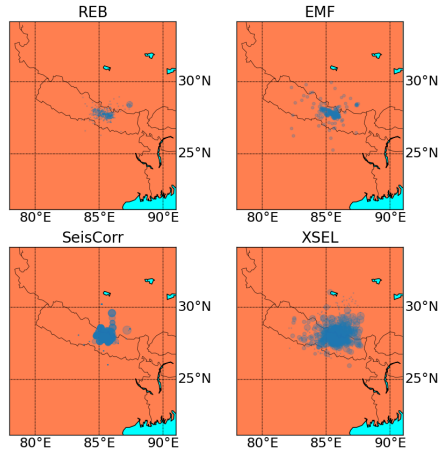
Analyst workload

Event locations

Epicenters (Tohoku)

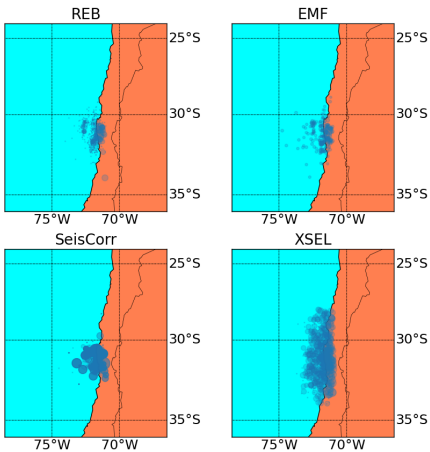


Epicenters (Nepal)

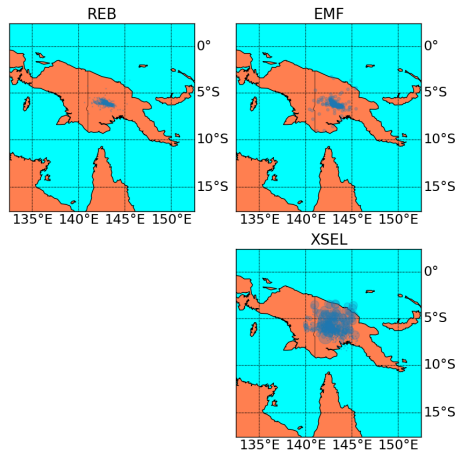


Event locations

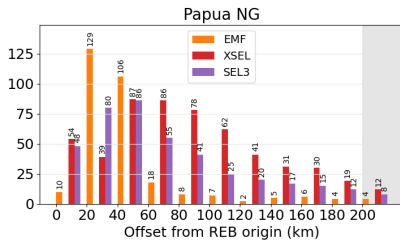
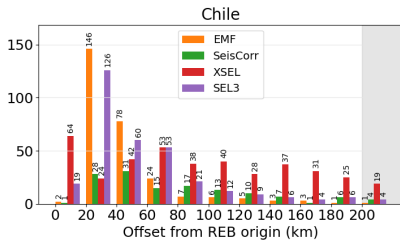
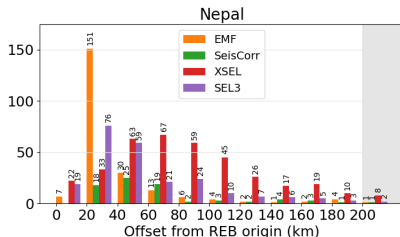
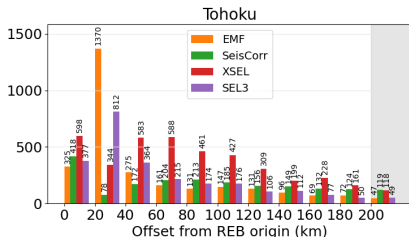
Epicenters (Chile)



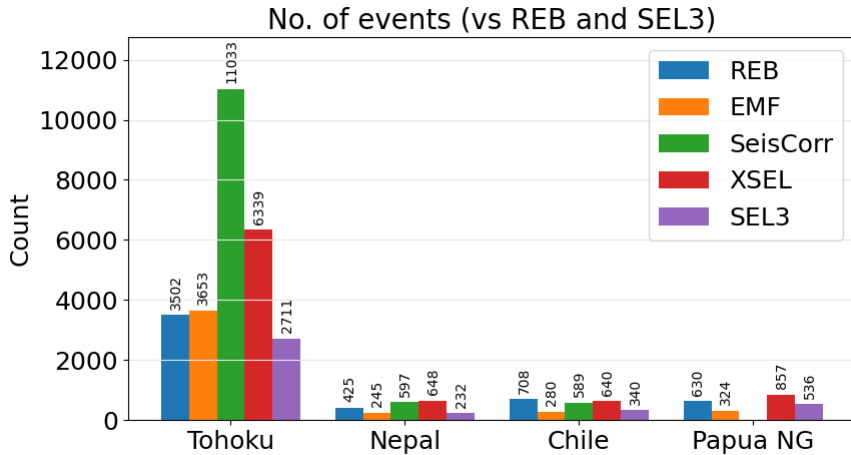
Epicenters (Papua NG)



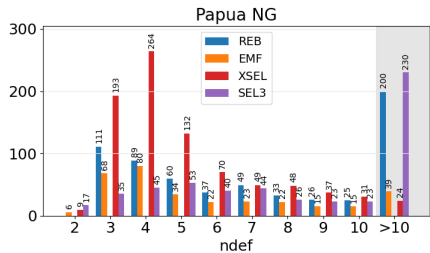
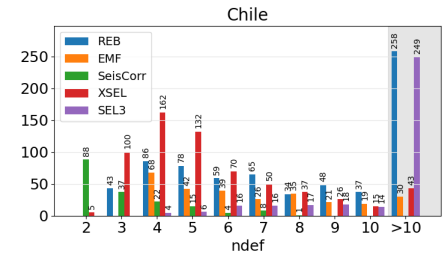
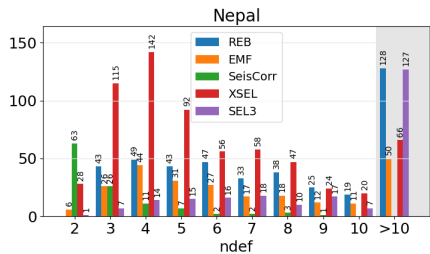
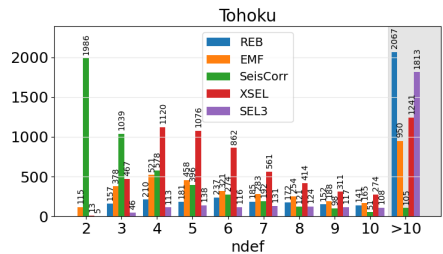
Distance from REB origins



Total no. of events



No. defining phases



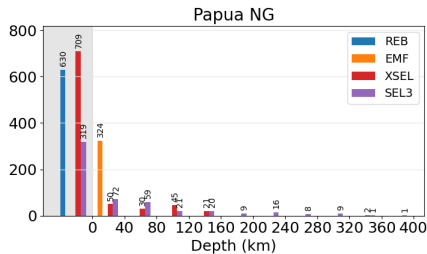
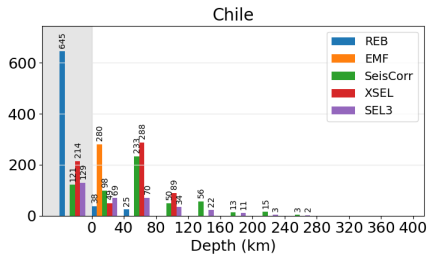
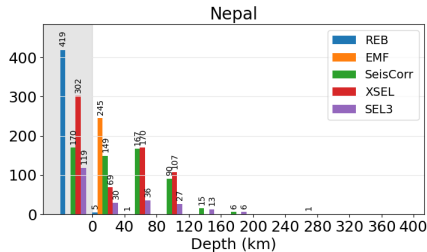
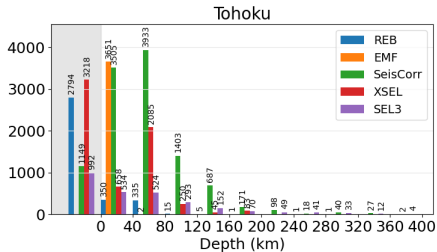
When the event depth is < 40 km or its uncertainty is large, depth is fixed to 0.

Lat/lon coordinates are changed accordingly so as event time and phase travel-times are consistent)

Matching events using location becomes tricky

⇒ Only arrival times are used to match events.

Estimated depths



- XSEL finds consistently many more events than all methods and REB
- EMF, SeisCorr and XSEL found more events than are listed in the REB for the Tohoku sequence
- EMF fixes all depths at 10 km
- SeisCorr defines many events with only 2 phases

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Common events¹: REB events sharing ≥ 2 time defining arrivals with an ALT event;
 $\text{REB} \cap \text{ALT}$ (TP)

Missed (added) events: REB events not in ALT; $\text{REB} \setminus \text{ALT}$ (FN)

False events: ALT events not in REB; $\text{ALT} \setminus \text{REB}$ (FP)

Split events: REB events sharing ≥ 1 time defining arrival with ≥ 2 ALT events;
 $\text{REB} \Rightarrow \text{ALT}$

Merged (joined) events: ALT events sharing ≥ 1 time defining arrival with ≥ 2 REB events;
 $\text{REB} \Leftarrow \text{ALT}$

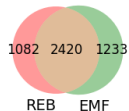
¹There are two commonality criteria: strong (distance between epicenters must be < 60 km) and weak (no distance limitation)

Common events:	$\frac{ REB \cap ALT }{ REB }$	(similar to recall/hit rate)
Missed (added) events:	$\frac{ REB \setminus ALT }{ REB }$	(=1 – recall)
False events:	$\frac{ ALT \setminus REB }{ ALT }$	(similar to false discovery rate)
Split events:	$\frac{ REB \Rightarrow ALT }{ REB }$	
Merged (joined) events:	$\frac{ REB \Leftarrow ALT }{ ALT }$	

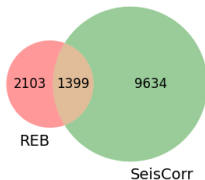
Standard metrics (weak)

Tohoku — REB events: 3502

Recall: 0.69
Precision: 0.66



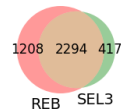
Recall: 0.40
Precision: 0.13



Recall: 0.83
Precision: 0.46

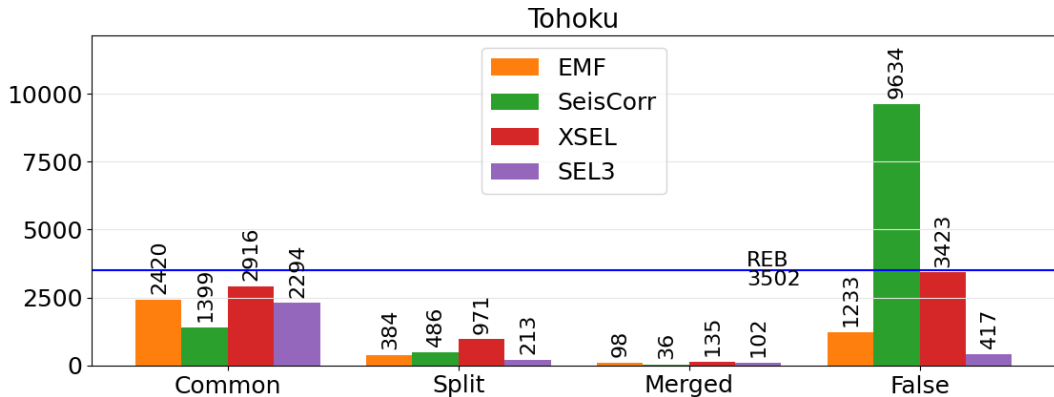


Recall: 0.66
Precision: 0.85

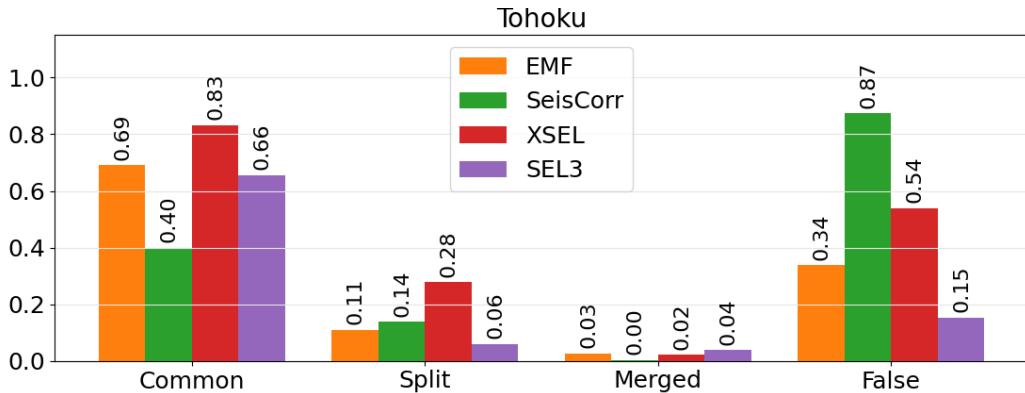


Missed by method Matched by method “False” events

Standard metrics (weak)



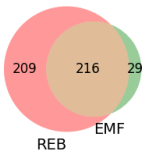
Standard metrics (weak)



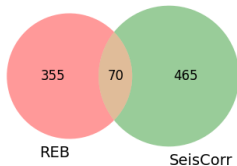
Standard metrics (weak)

Nepal — REB events: 425

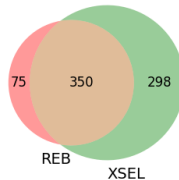
Recall: 0.51
Precision: 0.88



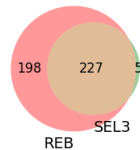
Recall: 0.16
Precision: 0.13



Recall: 0.82
Precision: 0.54

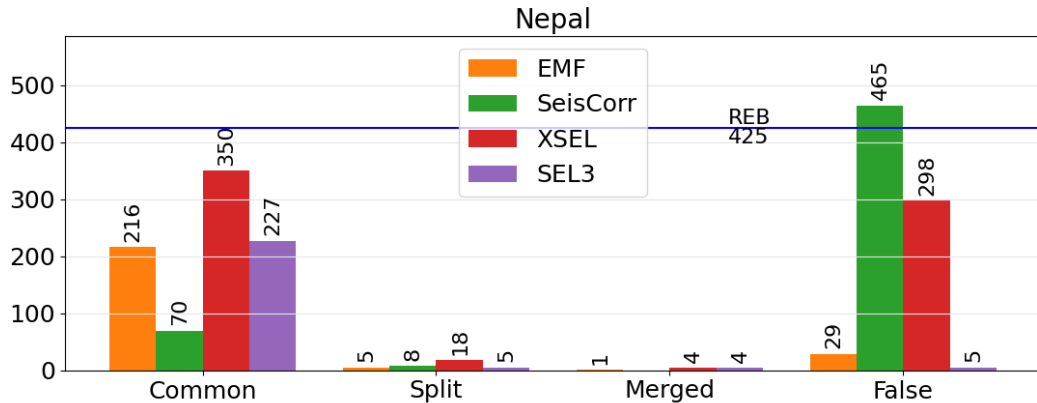


Recall: 0.53
Precision: 0.98

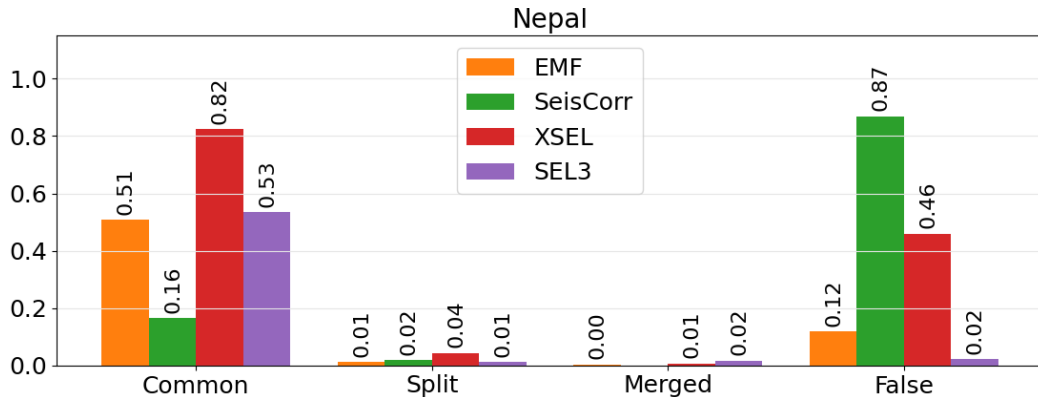


Missed by method Matched by method “False” events

Standard metrics (weak)

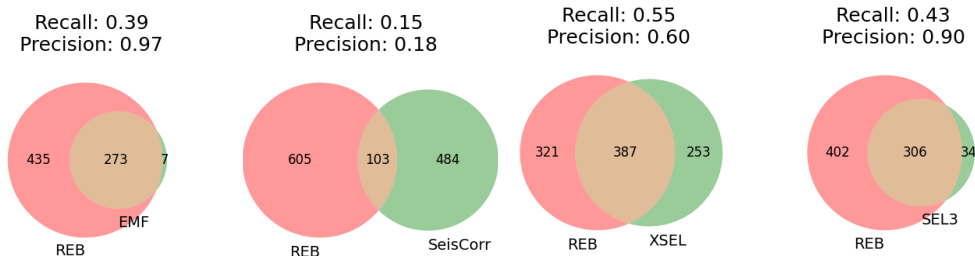


Standard metrics (weak)



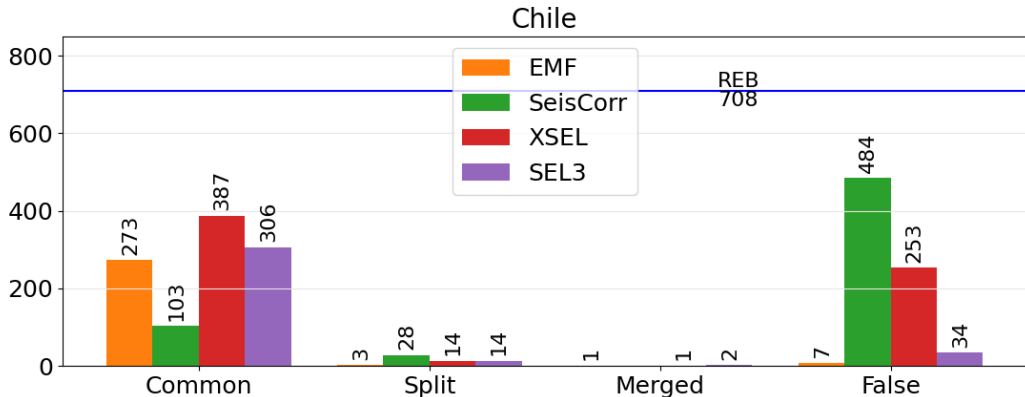
Standard metrics (weak)

Chile — REB events: 708

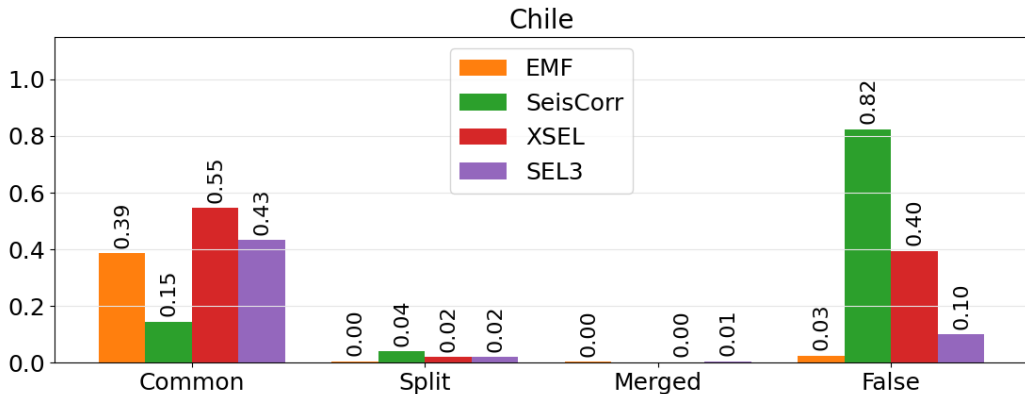


Missed by method Matched by method "False" events

Standard metrics (weak)



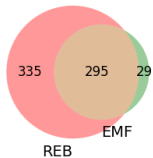
Standard metrics (weak)



Standard metrics (weak)

Papua NG — REB events: 630

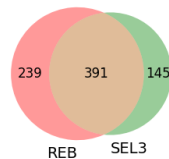
Recall: 0.47
Precision: 0.91



Recall: 0.84
Precision: 0.62

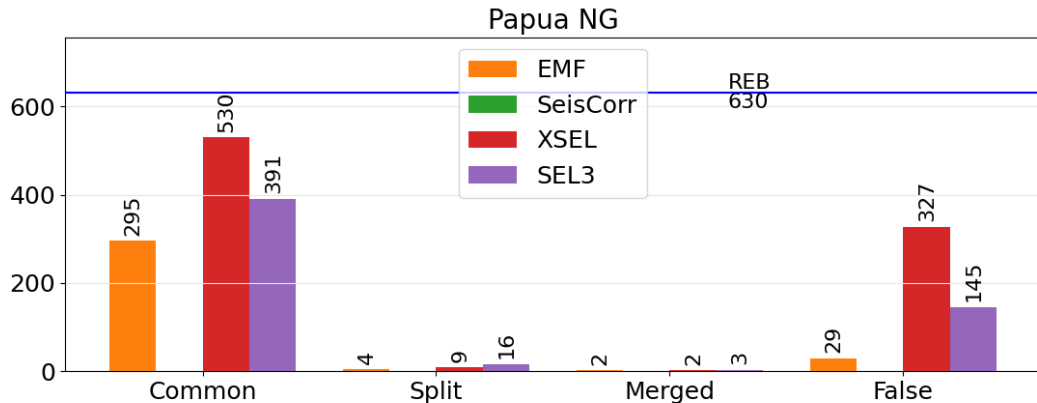


Recall: 0.62
Precision: 0.73

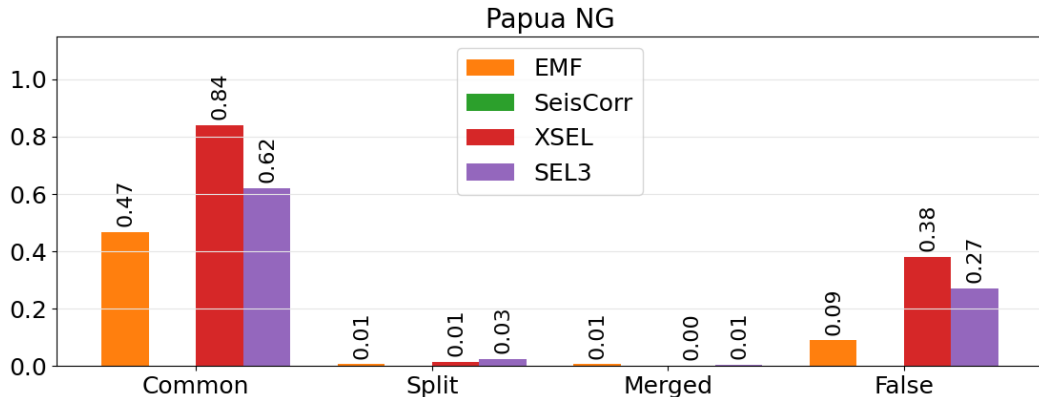


Missed by method Matched by method “False” events

Standard metrics (weak)



Standard metrics (weak)



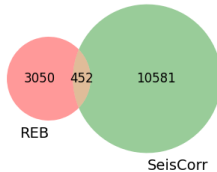
Standard metrics (strong)

Tohoku — REB events: 3502

Recall: 0.49
Precision: 0.47



Recall: 0.13
Precision: 0.04



Recall: 0.40
Precision: 0.22

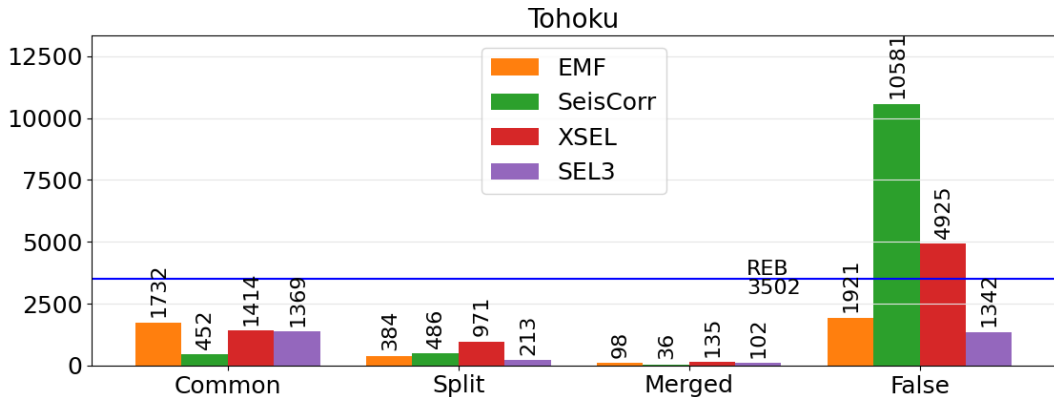


Recall: 0.39
Precision: 0.50

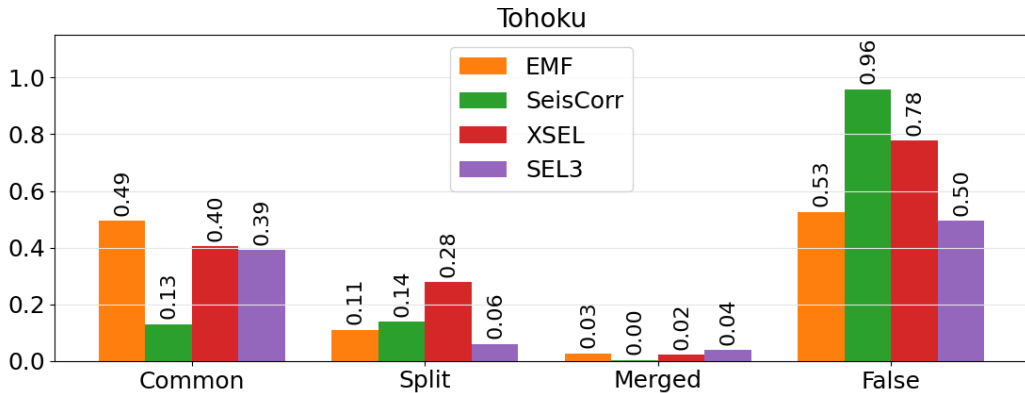


Missed by method Matched by method “False” events

Standard metrics (strong)



Standard metrics (strong)



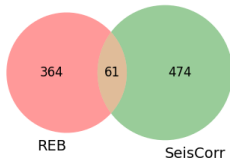
Standard metrics (strong)

Nepal — REB events: 425

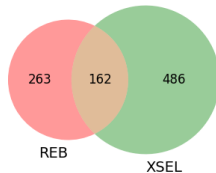
Recall: 0.46
Precision: 0.79



Recall: 0.14
Precision: 0.11



Recall: 0.38
Precision: 0.25

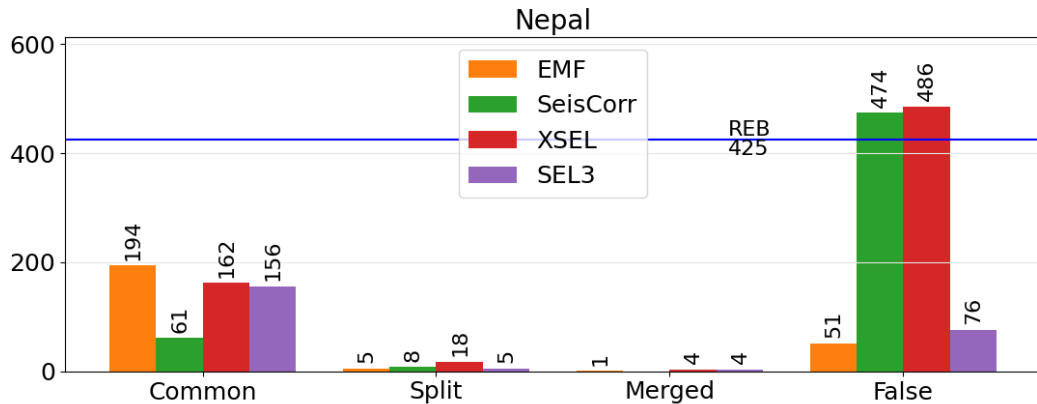


Recall: 0.37
Precision: 0.67

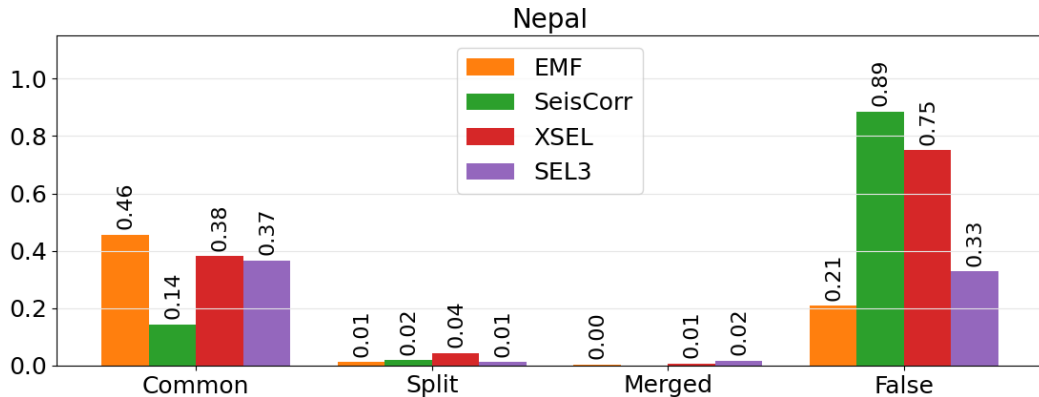


Missed by method Matched by method “False” events

Standard metrics (strong)



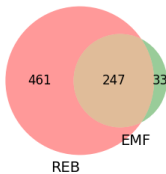
Standard metrics (strong)



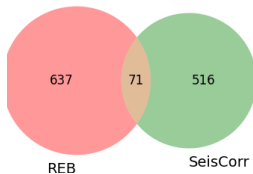
Standard metrics (strong)

Chile — REB events: 708

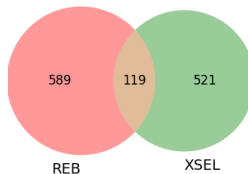
Recall: 0.35
Precision: 0.88



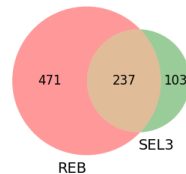
Recall: 0.10
Precision: 0.12



Recall: 0.17
Precision: 0.19

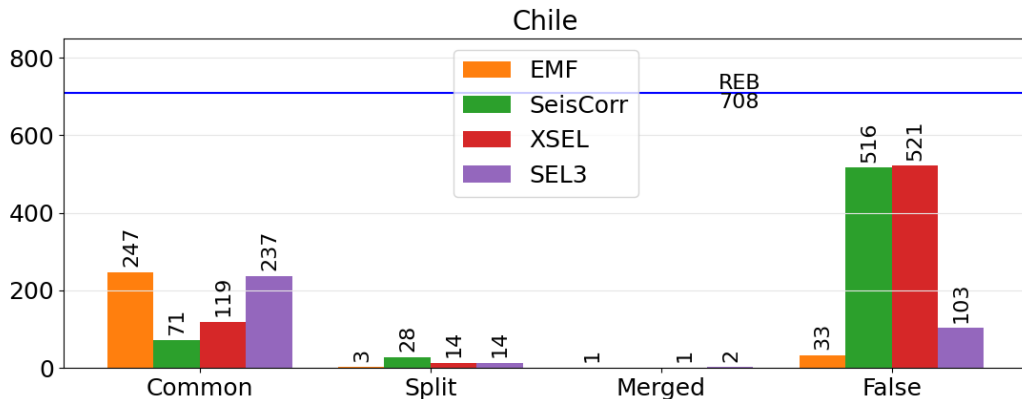


Recall: 0.33
Precision: 0.70

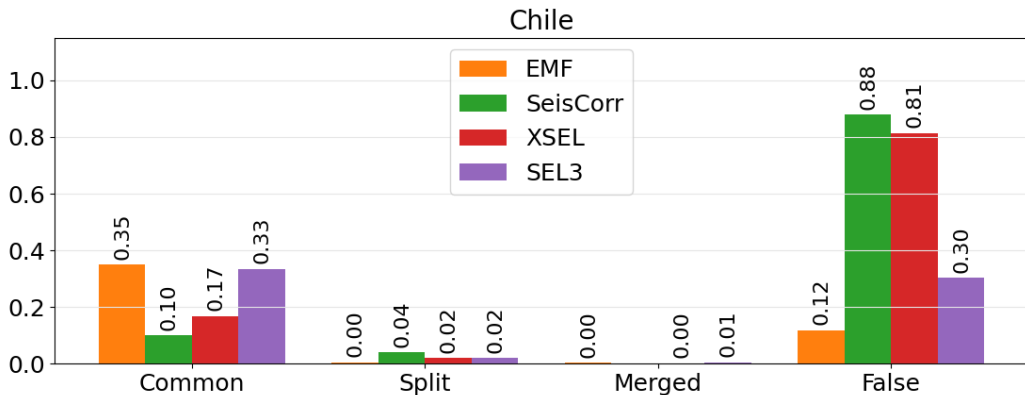


Missed by method Matched by method “False” events

Standard metrics (strong)



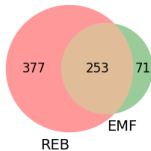
Standard metrics (strong)



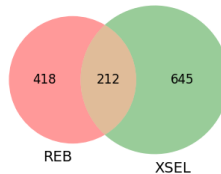
Standard metrics (strong)

Papua NG — REB events: 630

Recall: 0.40
Precision: 0.78



Recall: 0.34
Precision: 0.25

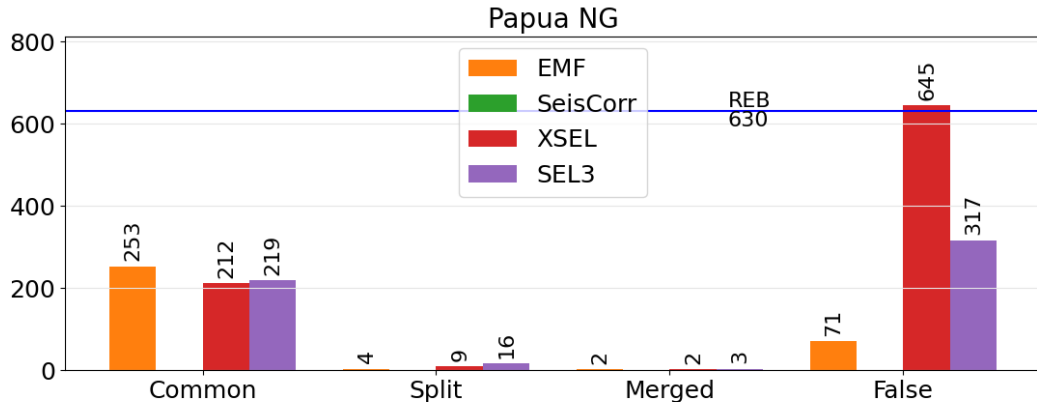


Recall: 0.35
Precision: 0.41

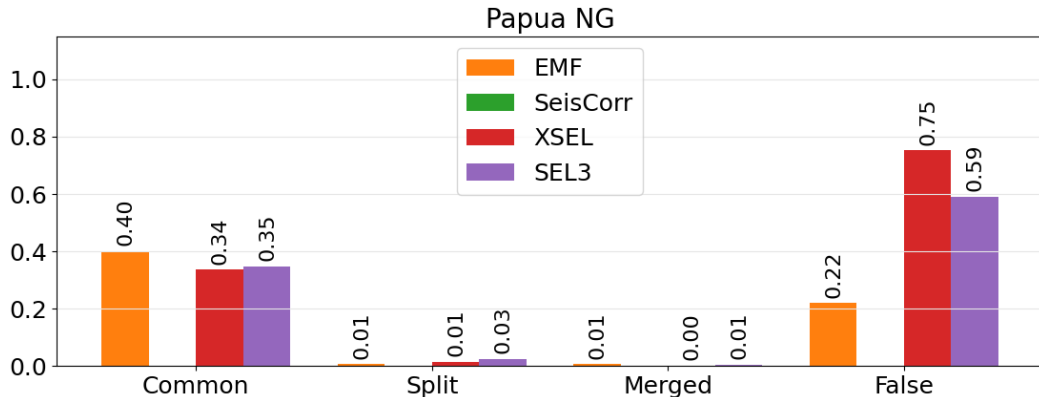


Missed by method Matched by method “False” events

Standard metrics (strong)



Standard metrics (strong)



Weak criterion

- EMF has consistently high precision, in some cases higher than SEL3 and comparable high sensitivity (recall) to SEL3
- XSEL has consistently high sensitivity (recall)
- EMF, SeisCorr and XSEL found more events than are listed in the REB for the Tohoku sequence

Strong criterion

- More or less the same conclusions but the figures are smaller

Overview of the IMS network and IDC pipeline

The project

Experiment constraints

Detection statistics

Event statistics

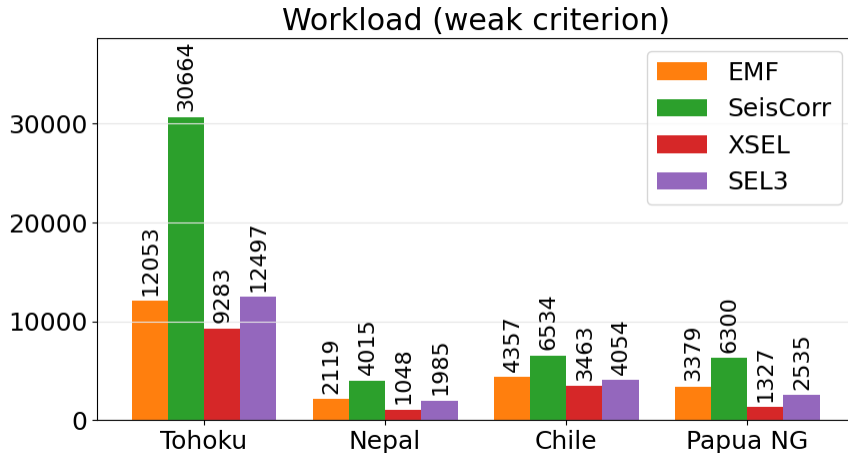
Bulletin comparison

Analyst workload

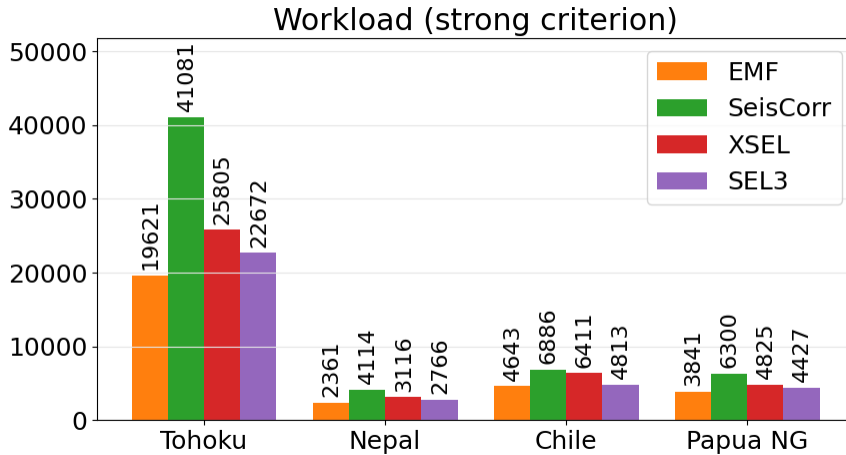
- There is not official/accurate way to calculate analyst workload
- A simple formula that has been regularly used
 - ignores fine tuning of events (e.g. retiming or renaming of arrivals)
 - assumes 1 missed event = 10 false events

Additional work load = false events + $10 \times$ missed events (work units)

Analyst workload (weak)



Analyst workload (strong)



- All three events show very good potential for use in the IDC pipeline
- Although SEL3 is extremely well fine tuned in some cases the methods even surpass SEL3 performance
- Workload for analysts is comparable to SEL3 workload
- When comparing with REB we should keep in mind
 - the REB is not 100% correct
 - the analysts are shown SEL3 events; anchoring phenomenon may occur

- Combine these methods with the conventional pipeline that generates SEL3
- Test these methods with mining events
- Have analysts review events automatically produced by these methods
- More accurately estimate the analyst workload



Vienna International Centre, PO Box 1200
1400 Vienna, Austria
CTBTO.ORG