AWE NUCLEAR SECURITY TECHNOLOGIES

Infrasound Arrivals in the International Data Centre Bulletins: Reviewing 14 years of Results and Celerity-Range Model Changes

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Motivation

- Analysis of the Bering Bolide 2018-12-18 event in the Reviewed Event Bulletin (REB) of the International Data Centre (IDC), identified a faster celerity than expected (349 m/s) for the I44RU detection at a distance of ~1000 km from the REB origin.
- The celerity-range model used by the IDC for the location of this event was not the Brachet et al. (2010) model.
- Analysis of the celerity-range model used by the IDC through time (2010-2024) identifies model changes in May-2017 and again in August-2020.
- Here we investigate the impact of these changes on detections and event locations.

Some Terminology

- SEL3 – Standard Event List 3
  - Three automatic bulletins are produced by the IDC, referred to as Standard Event Lists (SELs). These SELs are progressively more delayed from real-time (1, 4, and 6 hours for SEL1, SEL2 and SEL3 respectively) and thus contain increasingly refined event locations as additional data arrive at the IDC.

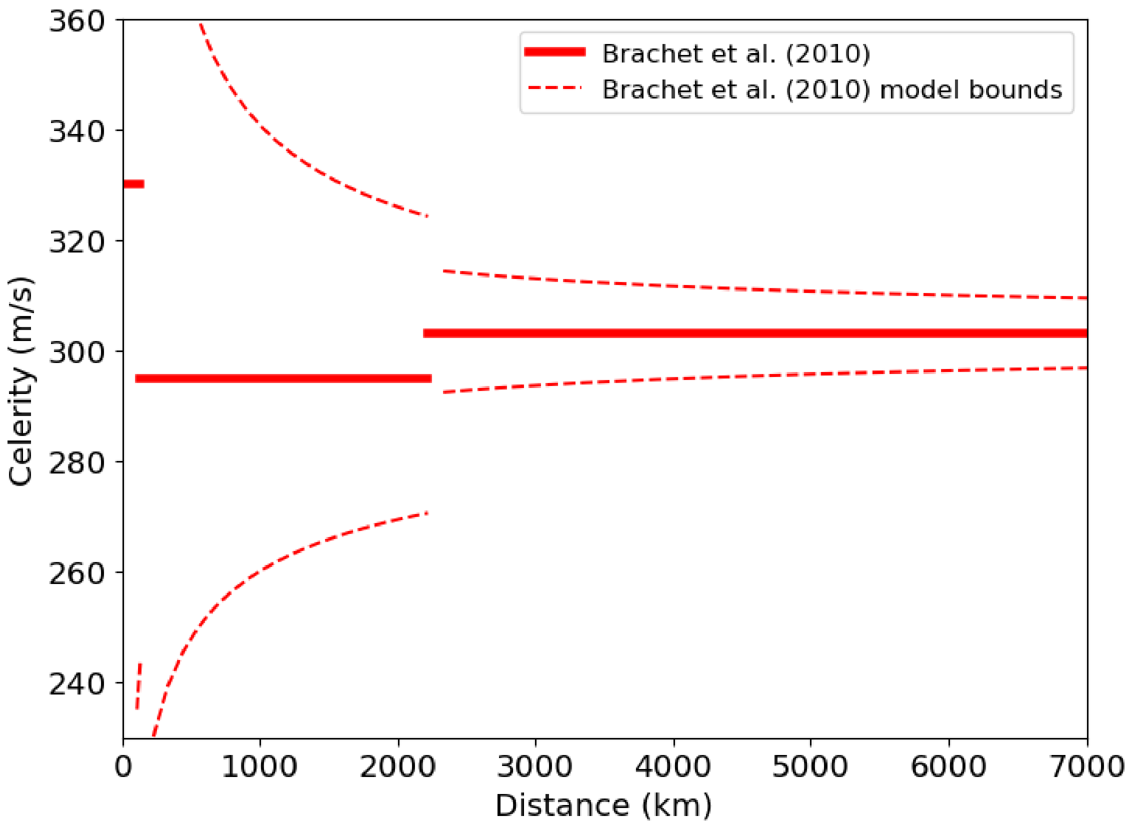
- REB – Reviewed Event Bulletin
  - The SEL3 is reviewed by analysts, who may correct the automatic results or add any detections made on late arriving data not available during SEL3 processing, to produce the REB, noting that REB events must meet the IDC event definition criteria.

- LEB – Late Event Bulletin
  - The LEB is the complete bulletin created after review by analysts, noting that events do not have to fulfil the IDC event definition criteria, e.g., 2-station infrasound only events are included in the LEB.

Le Bras et al. (2021)

IDC Celerity-range model changes

2010-2024

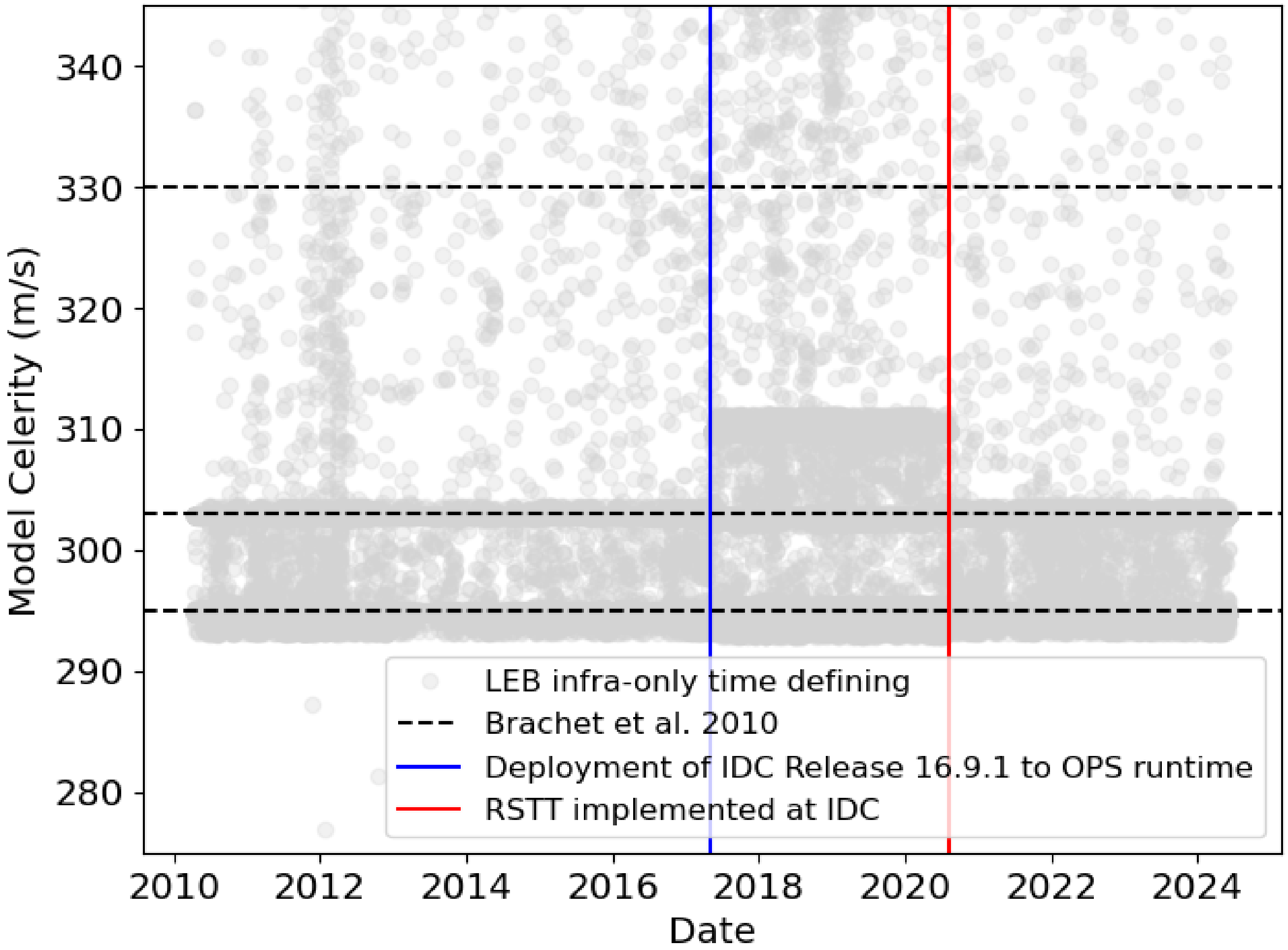


LEB Infrasound-only events, time-defining arrivals

$$model\ celerity = \frac{source{-}to{-}receiver\ range}{(arrival\ time - origin\ time) - (travel\ time\ residual)}$$

- Scatter in the model celerity is due to associated detections at distances around the model boundaries, e.g., in the Brachet et al. (2010) model, at 1.2° and 20° distance.

- Between 2017 and 2020, the model celerity changes.



Regional Seismic Travel-Time (RSTT) model (Myers et al., 2010)

LEB Seismo-acoustic events, time-defining arrivals

$$model\ celerity = \frac{source{-}to{-}receiver\ range}{(arrival\ time - origin\ time) - (travel\ time\ residual)}$$

- Scatter in the model celerity is due to associated detections at distances around the model boundaries, e.g., in the Brachet et al. (2010) model, at 1.2° and 20° distance.

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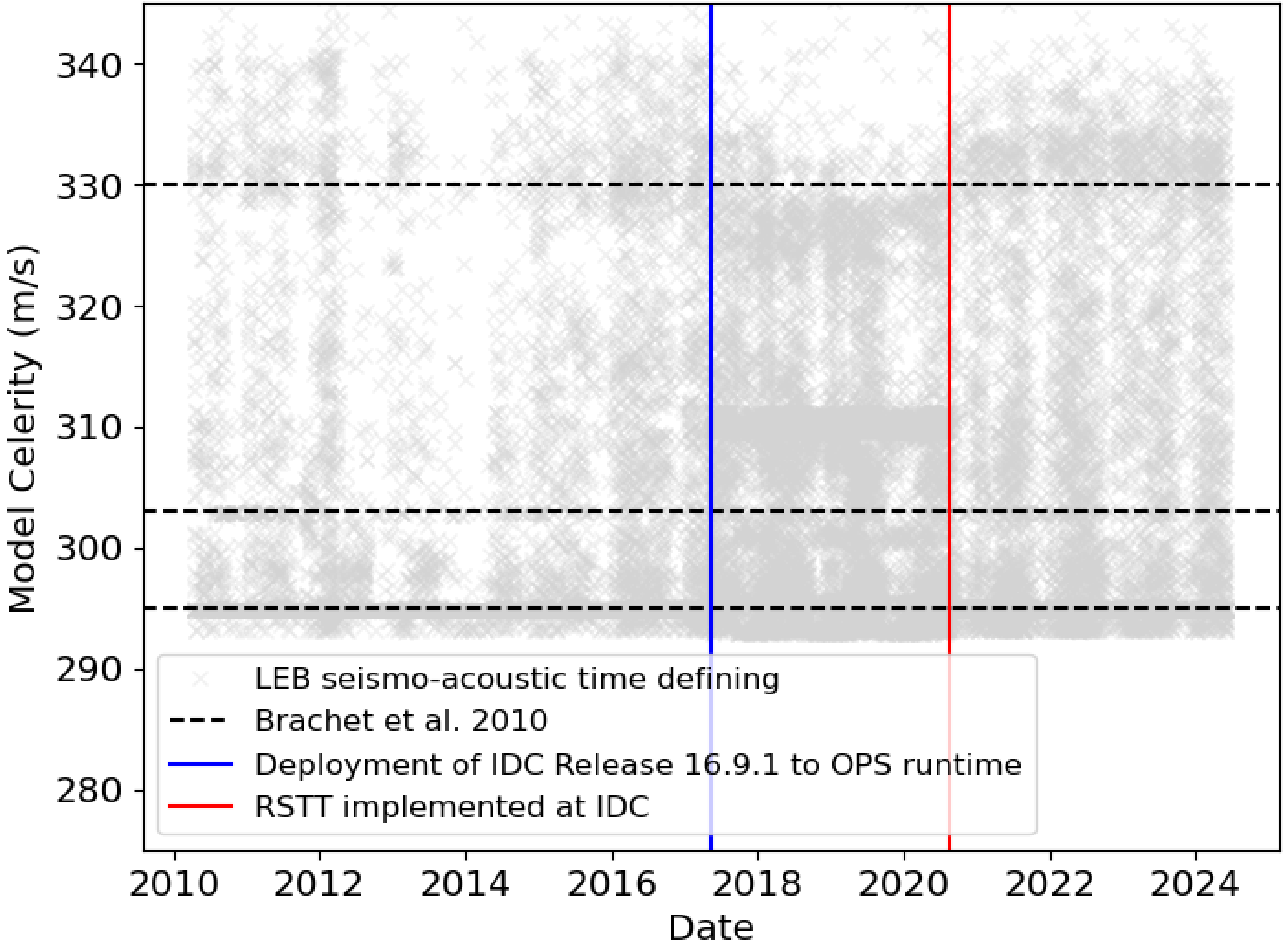
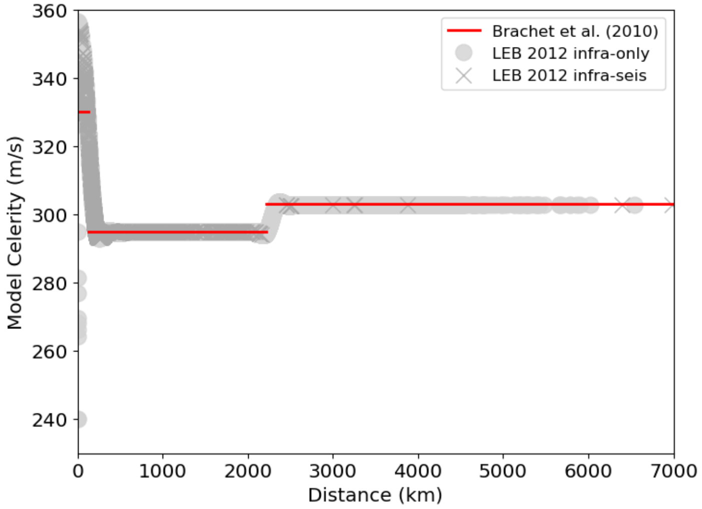


Regional Seismic Travel-Time (RSTT) model (Myers et al., 2010)

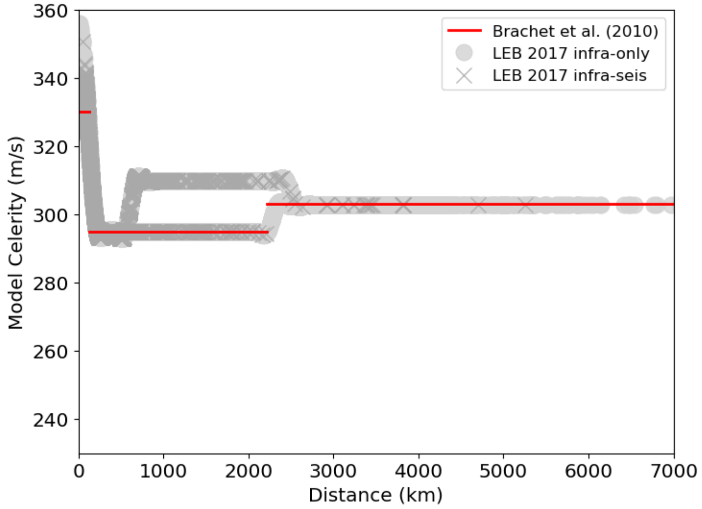
LEB events, time-defining arrivals

$$model\ celerity = \frac{source\text{—}to\text{—}receiver\ range}{(arrival\ time - origin\ time) - (travel\ time\ residual)}$$

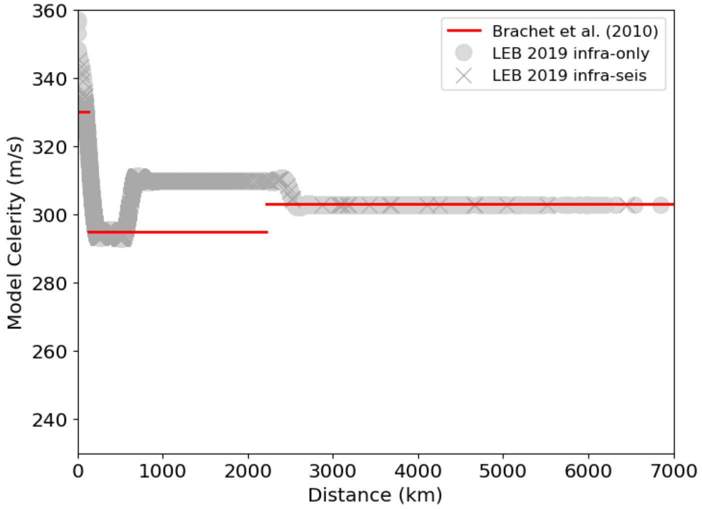
2012



2017



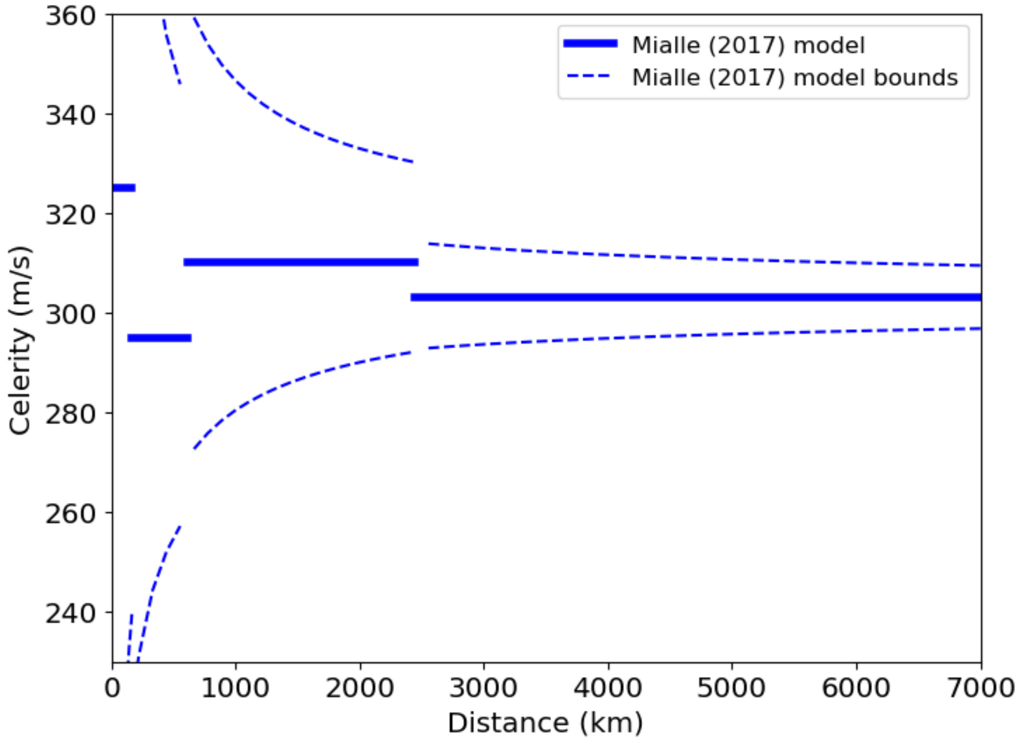
2019



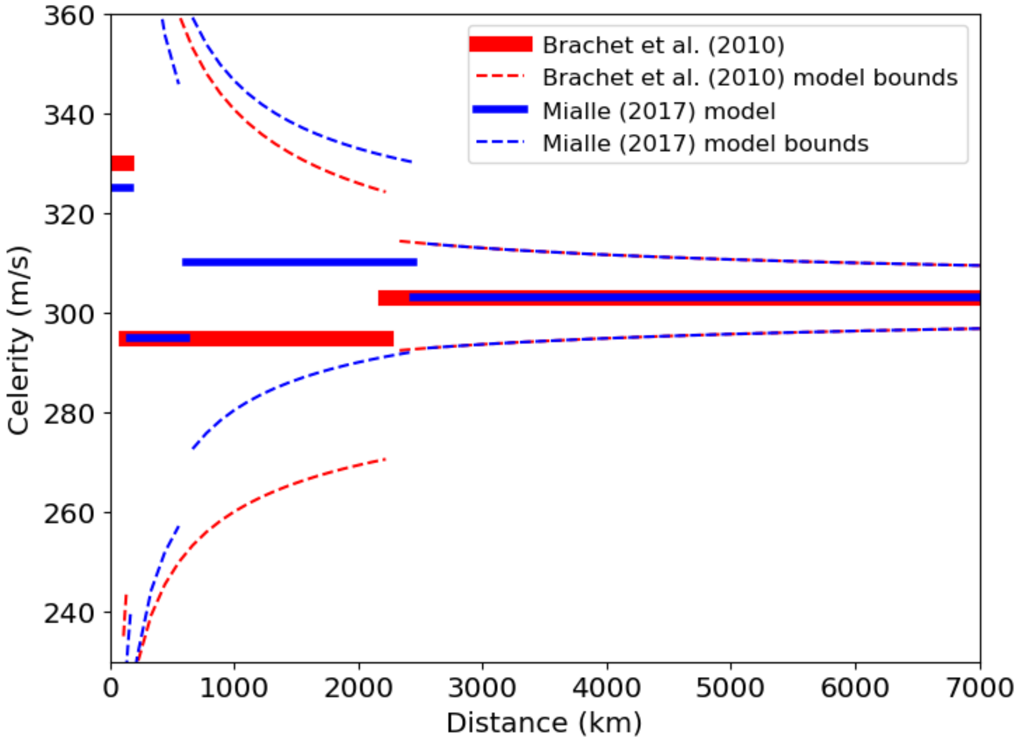
- The scatter in the model celerity observed on the previous two slides is due to associated detections at distances around the model boundaries, e.g., in the Brachet et al. (2010) model, at 1.2° and 20° distance. These gradients can be seen here.

IDC config file analysis

- Between May-2017 and Aug-2020, the model below is used



- From the IDC config files, pre-May-2017 and post-Aug-2020, the model used is the Brachet et al. (2010) model



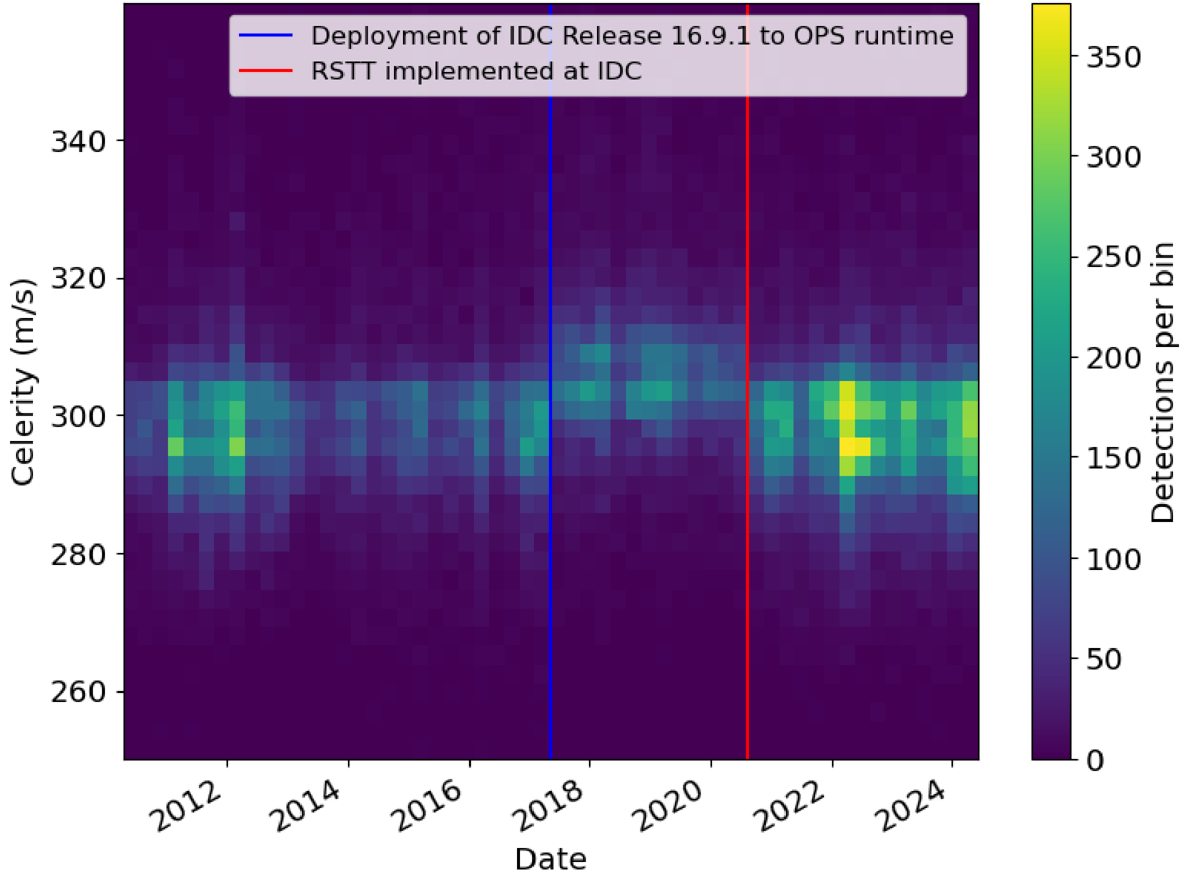
IDC Celerity-range model changes – impact on the celerities of associated detections?

2010-2024

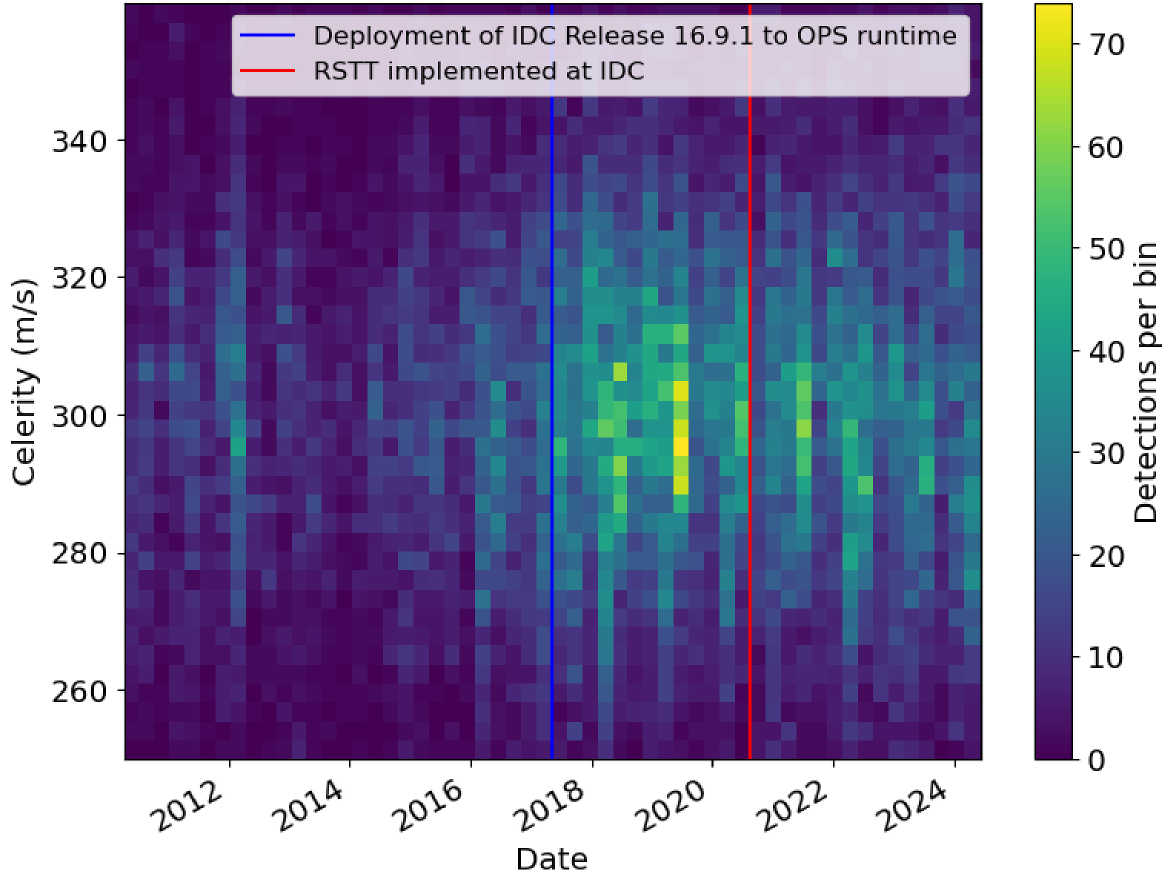
$$celerity = \frac{source\text{–}to\text{–}receiver\ range}{(arrival\ time - origin\ time)}$$

Impact on celerities of associated time-defining detections through time

- Infrasound-only events (LEB)



- Seismo-acoustic events (LEB)

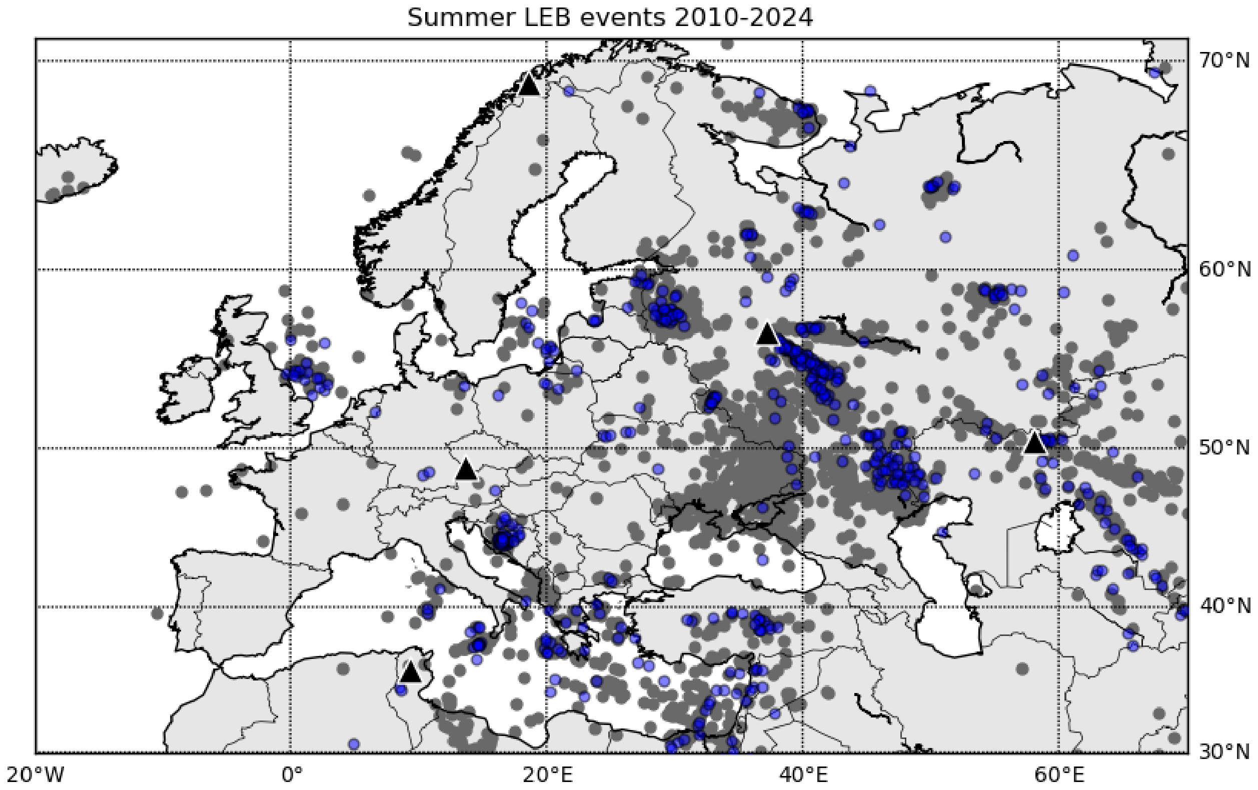


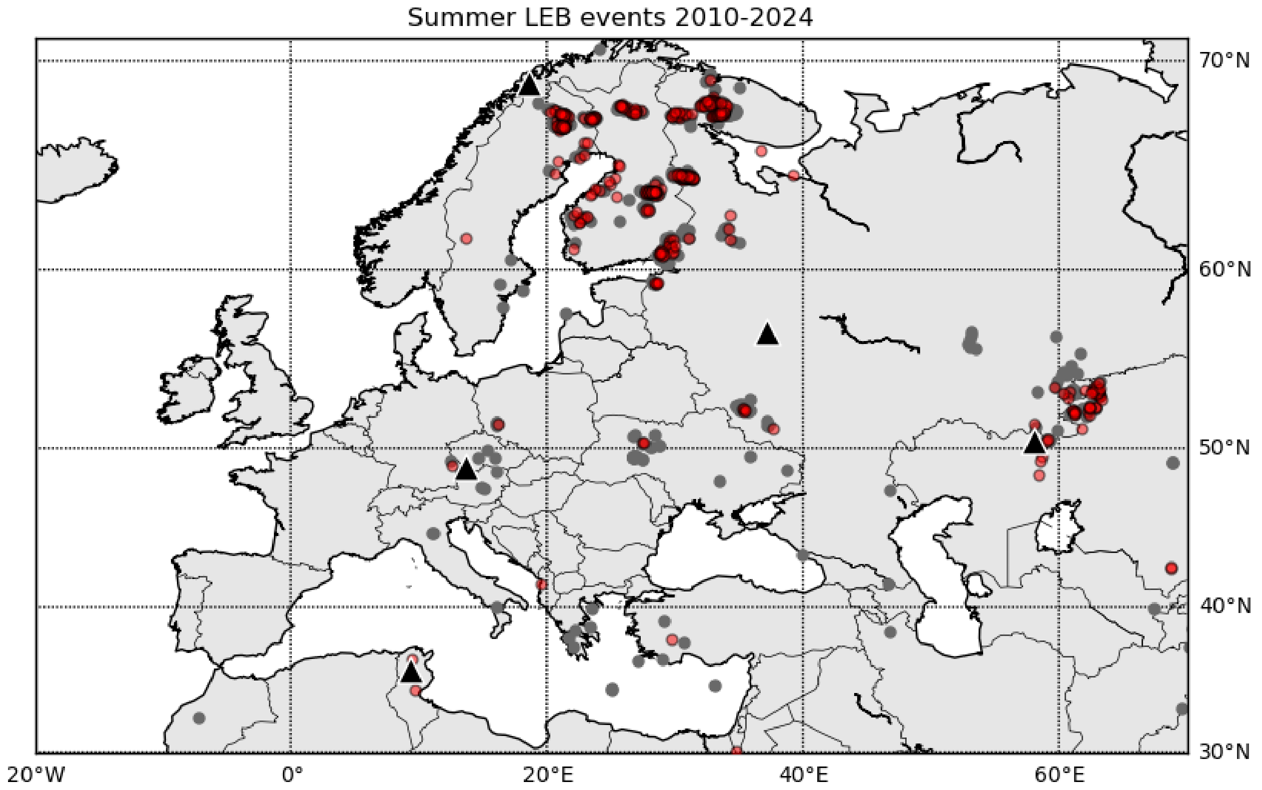
- Bin-size is 2.75m/s and ~3 months

IDC Celerity-range model changes – impact on event locations?

2010-2024

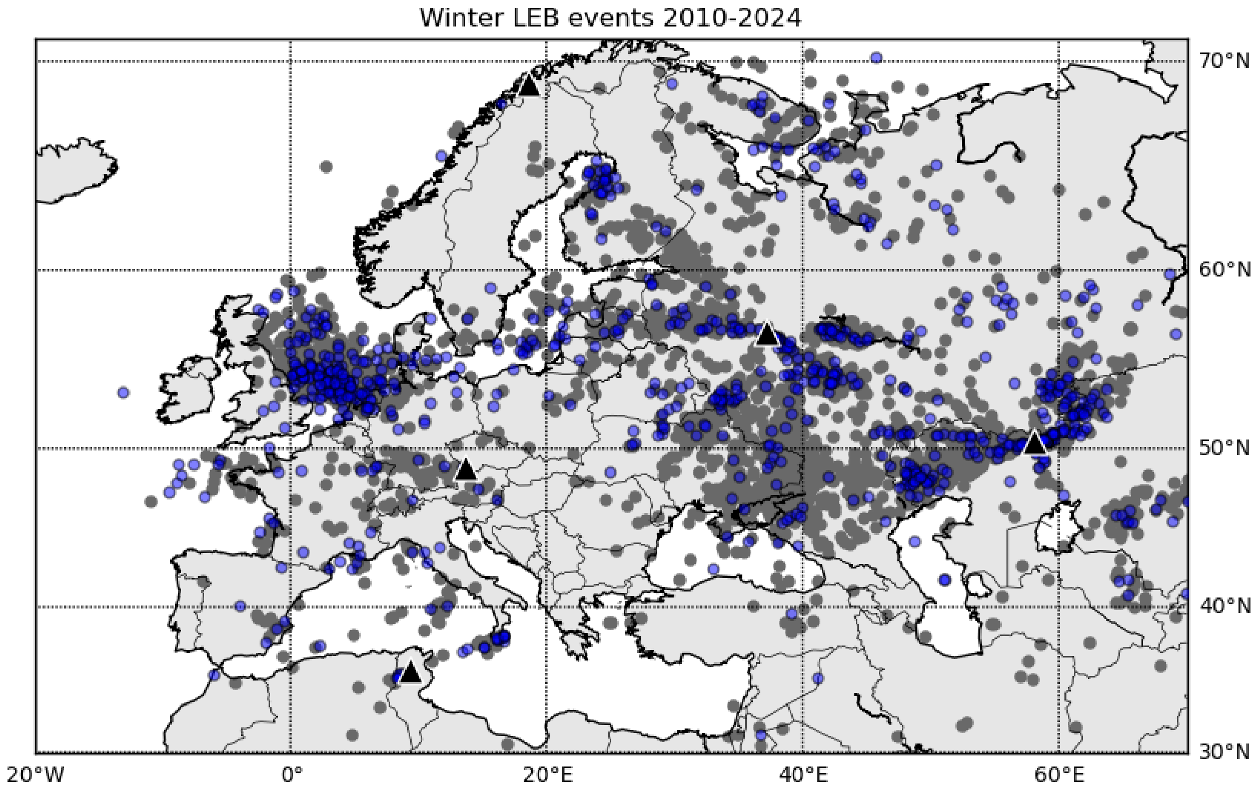
Event clusters

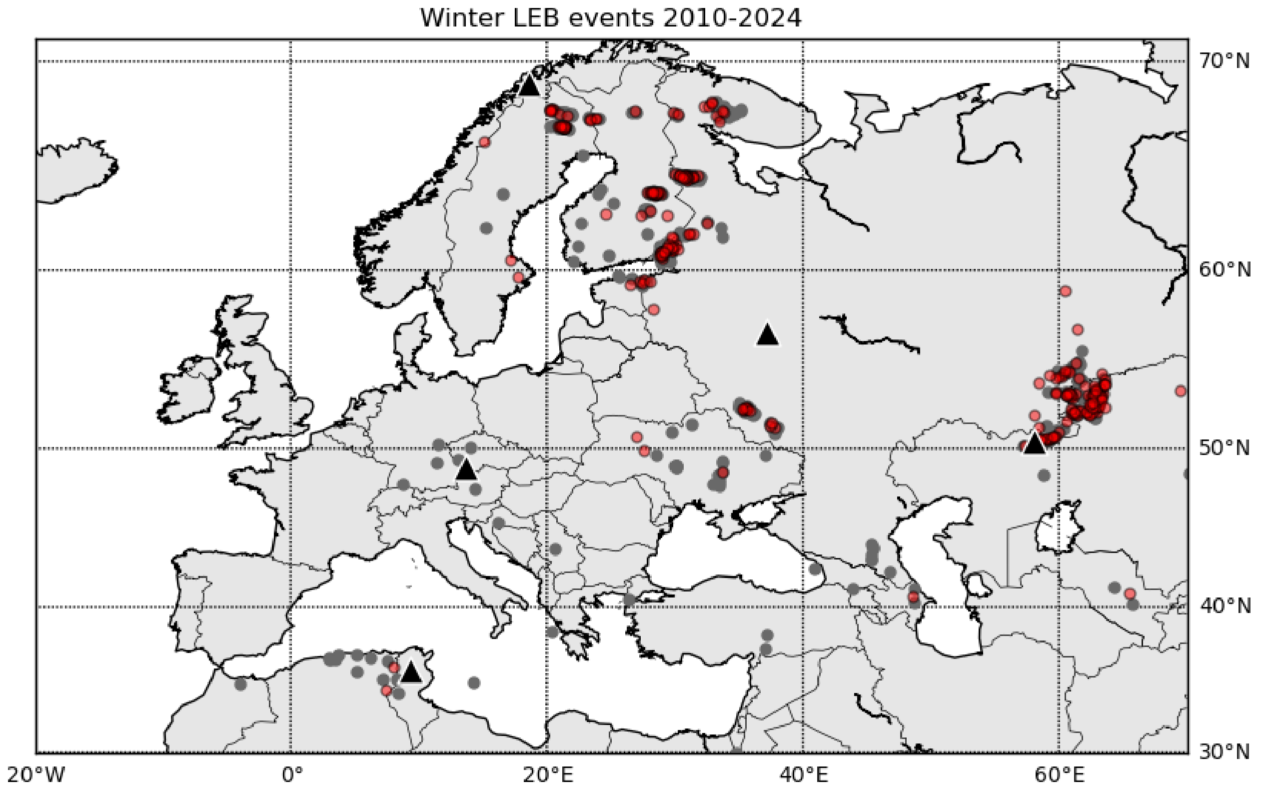




- Infrasound-only
  - Dark grey circles (Brachet et al. (2010): 2010-2016 and 2021-2024)
  - Blue circles (Mialle (2017): 2018 and 2019)
- Seismo-acoustic
  - Dark grey circles (Brachet et al. (2010): 2010-2016 and 2021-2024)
  - Red circles (Mialle (2017): 2018 and 2019)

Event clusters





- Infrasound-only
  - Dark grey circles (Brachet et al. (2010): 2010-2016 and 2021-2024)
  - Blue circles (Mialle (2017): 2018 and 2019)
- Seismo-acoustic
  - Dark grey circles (Brachet et al. (2010): 2010-2016 and 2021-2024)
  - Red circles (Mialle (2017): 2018 and 2019)

North Sea event clusters

- No systematic variations in source-to-receiver distance to I26DE, I43RU, I31KZ or I37NO were observed through time for events within the North Sea area.

- For events where the majority of arrivals are at distances of ~2000 km, e.g, North Sea, the change to the Mialle (2017) velocity model (with faster celerities) is likely to cause an approximate shift of the origin time to 5 minutes later than estimated using the Brachet et al. (2010) velocity model (if it is assumed that the lat/lon of the location is predominantly controlled by the intersection of azimuth estimates).

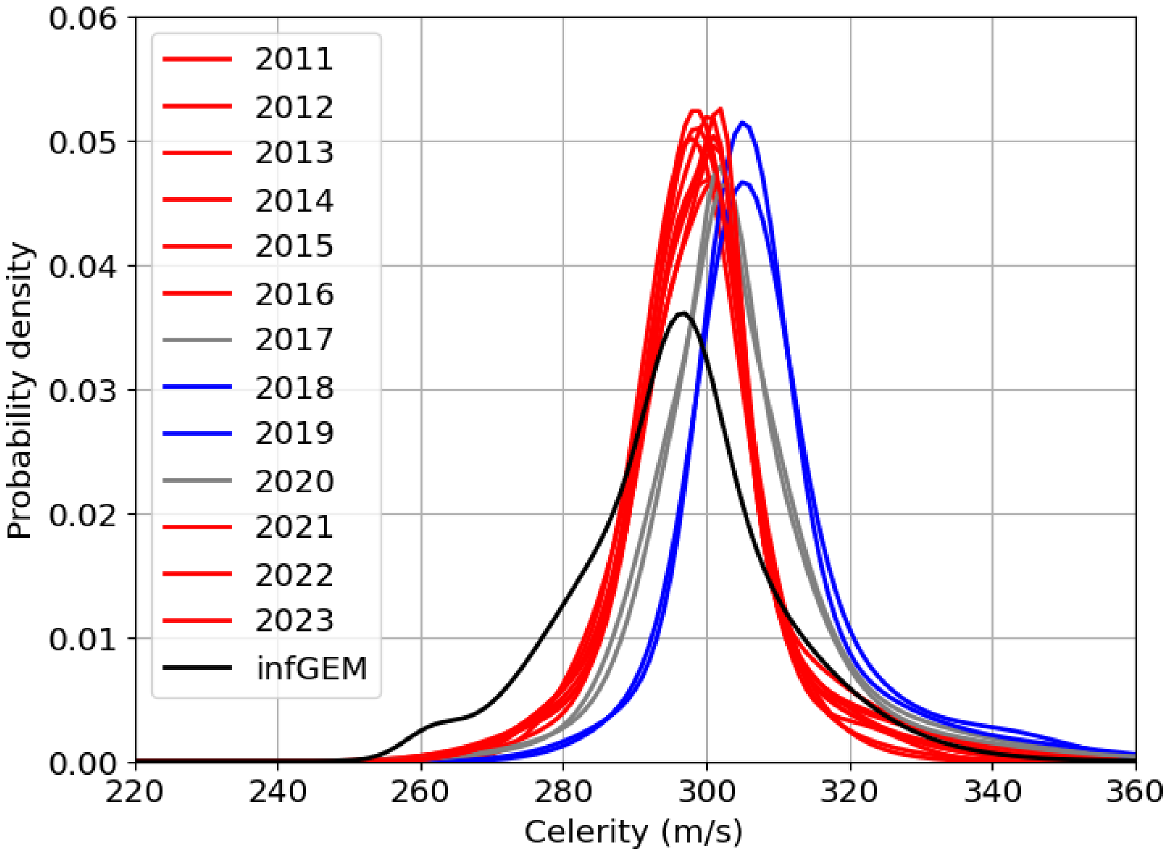
Locating ground truth events using InfraPy and a selection of Gaussian Mixture Models (GMMs) (Blom et al., 2020)

Three case studies: Beirut, Sayarim and the Bering Bolide

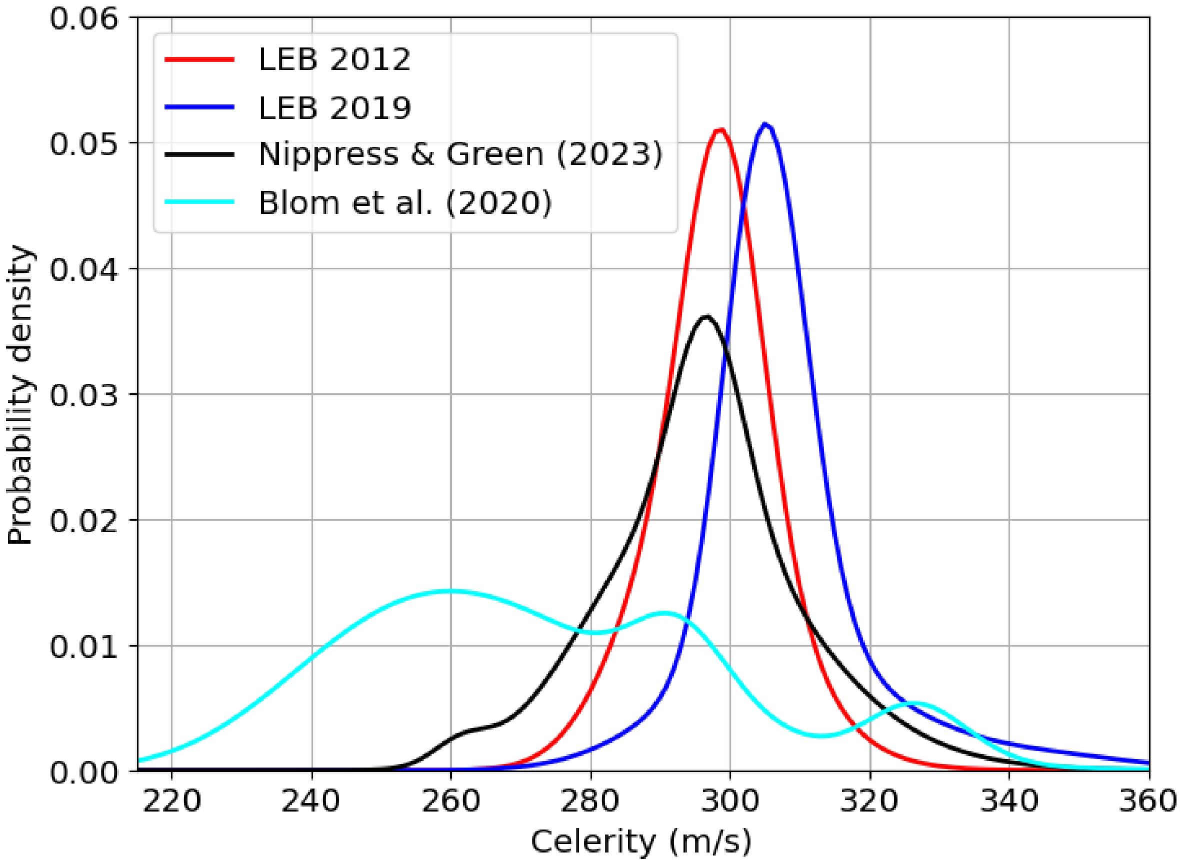
InfraPy DOI: 10.5281/zenodo.7116991

Gaussian Mixture Models (GMMs)

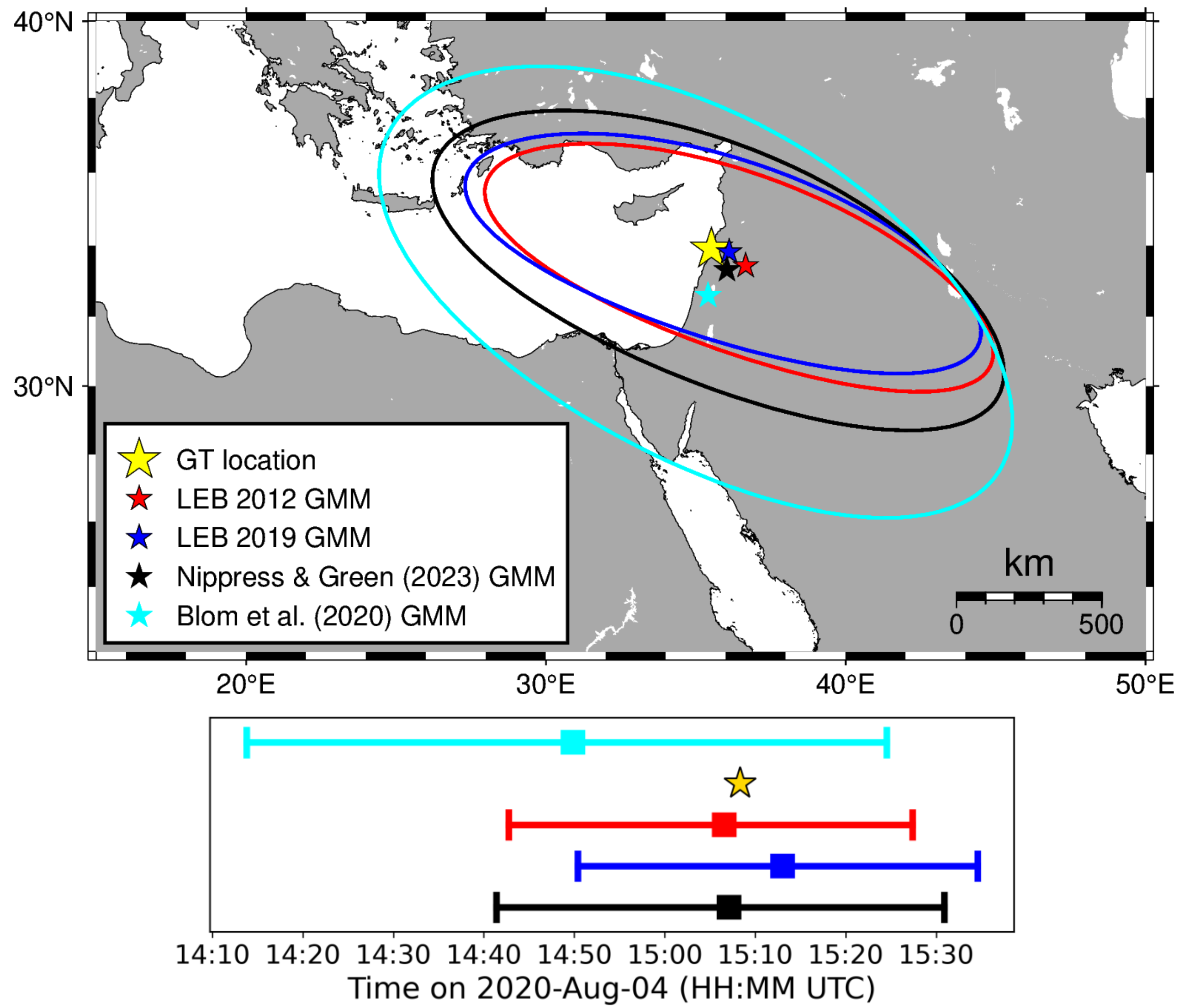
- GMMs for whole years of LEB detections, 2011-2023



- GMMs used in this study
  - LEB 2012 is used to represent the Brachet et al. (2010) model
  - LEB 2019 is used to represent the Mialle (2017) model



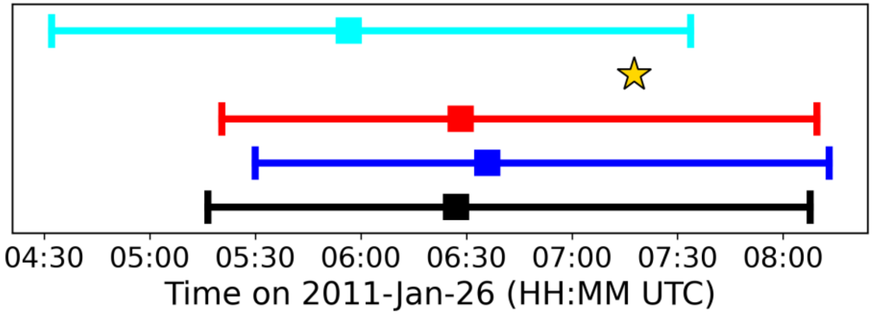
Event 1: Beirut, 2020-Aug-04

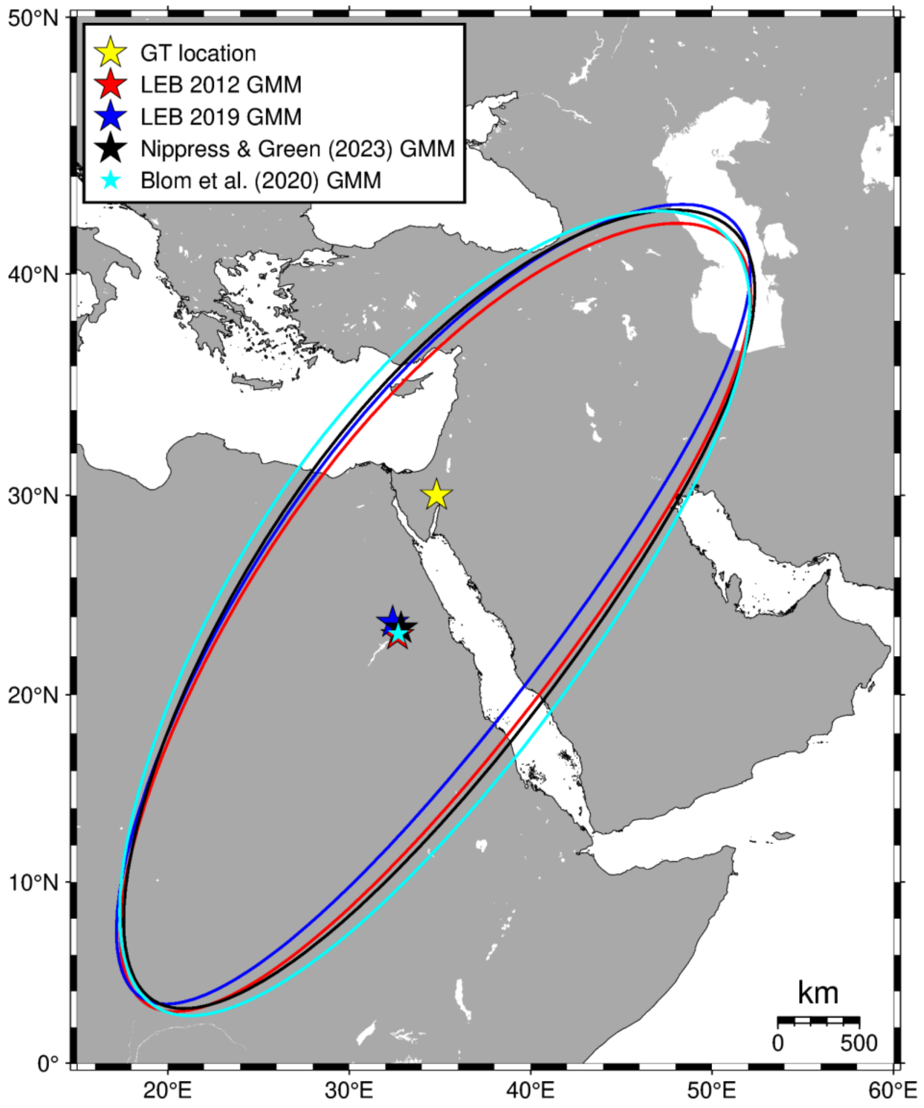


- Ground truth location is within the 95% confidence ellipse for all 4 models shown
- Ground truth origin time is within the 90% confidence bounds for all 4 models shown
- Detections are taken from Nippress & Green (2023) and are all to the west of the event:
  - I48TN, Tunisia, 2398 km
  - I26DE, Germany, 2450 km
  - I17CI, Ivory Coast, 5129 km
  - I42PT, Azores, 5606 km

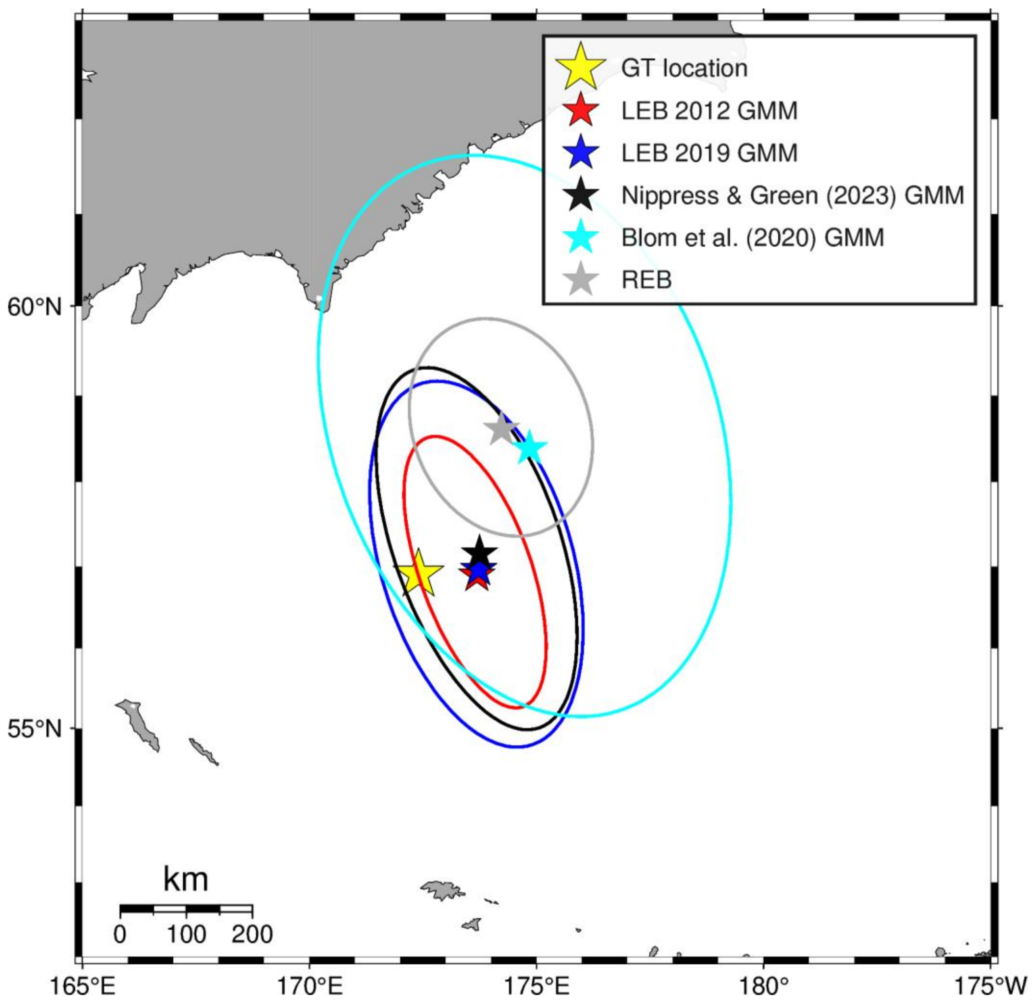
Event 2: Sayarim, 2011-Jan-26

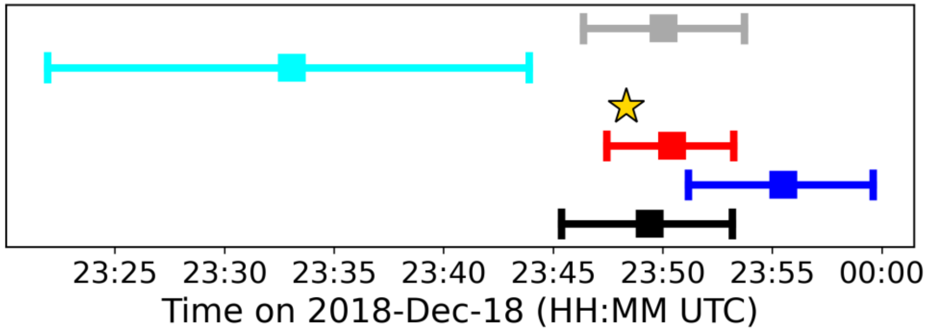
- Ground truth location is within the 95% confidence ellipse for all 4 models shown
- Ground truth origin time is within the 90% confidence bounds for all 4 models shown
- Detections are taken from Nippress & Green (2023) and are all to the east of the event:
  - I31KZ, Kazakhstan, 2982 km
  - I46RU, Russia, 4784 km
  - I34MN, Mongolia, 6279 km





Event 3: Bering bolide, 2018-Dec-18





- Ground truth location is within the 95% confidence ellipse for all 4 of the GMMs
- Ground truth origin time is within the 90% confidence bounds for 2 of the 4 GMMs
- Detections are taken from Grant et al. (2024). There are 11 detections providing good azimuthal coverage: I44RU, I53US, I30JP, I56US, I59US, I46RU, I10CA, I37NO, I43RU and I26DE and observations at distances from ~1000 km to ~8000 km.

Summary of Event Location Case-Studies

- Events with large azimuthal gaps produce similar locations and origin times for all four GMMs used in this study.

- Events with small azimuthal gaps allow the differences in the celerity model GMMs to become apparent:

  - For the Bering bolide event, this leads to two of the GMMs not constraining the ground truth OT within their 90% OT confidence bounds.

Summary

- We identified that the celerity-range model in use at the IDC changed in May 2017 and then reverted to its original model in August 2020.
- The impact of these changes on detections is such that there is an overall increase in the celerity of associated detections between 2017-May and 2020-Aug (see slide 9).
- The impact of these changes on event location clusters, i.e., large scale trends, appears to be minimal.
- The impact of these changes on individual ground truth events appears to be minimal for events with observations all to one side (i.e., large azimuthal gap), but may have an impact for events with a small azimuthal gap. Further investigation is required.
- Future work – need to consider how best to improve locations for infrasound-only events through celerity models? Combination of empirical models and ‘real-time’ propagation modelling?

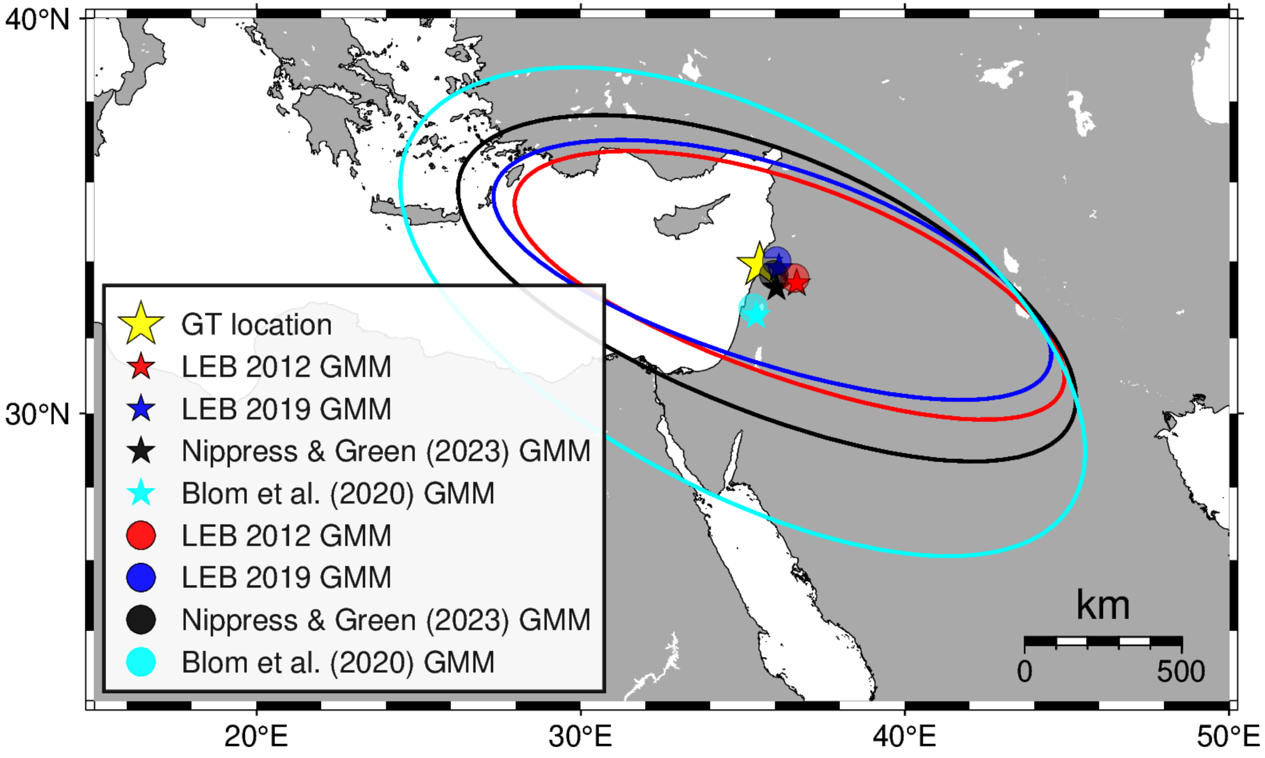
References

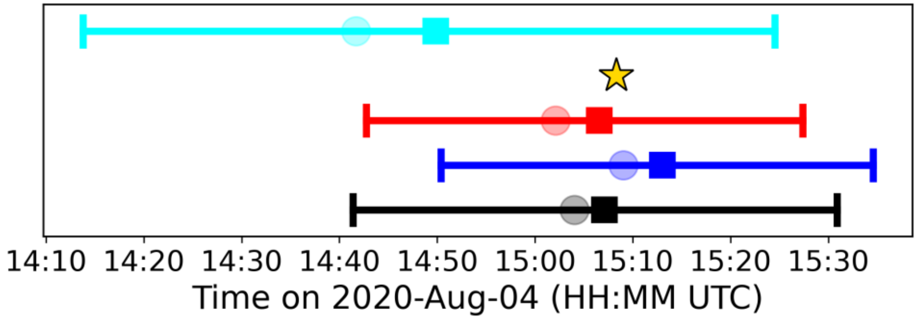
- Blom, P., Euler, G., Marcillo, O. and Dannemann Dugick, F., (2020). Evaluation of a pair-based, joint-likelihood association approach for regional infrasound event identification, *Geophysical Journal International,* **221**, 1750-1764, doi: 10.1093/gji/ggaa105
- Brachet, N., Brown, D., Le Bras, R., Mialle, P. and Coyne, J., (2010). Monitoring the Earth's atmosphere with the Global IMS Infrasound Network, in *Infrasound Monitoring for Atmospheric Studies,* pp. 77-118, Springer, Dordrecht, ISBN:978-1-4020-9507-8.
- Grant, B., Nippress, A. and Green, D., (2024). Infrasound analysis of the 2018-Dec-18 49 kiloton Bering Sea bolide: Misassociations and celerity-range models, *Proceedings of Meetings on Acoustics,* **54** (1), 045003, doi: 10.1121/2.0001943.
- Le Bras, R., Arora, N., Kushida, N., Mialle, P., Bondár, I., Tomuta, E., Alamneh, F.K., Feitio, P., Villarroel, M., Vera, B., Sudakov., A., Laban, S., Nippress, S., Bowers, D., Russell, S. and Taylor, T., (2021). NET-VISA from cradle to adulthood. A machine-learning tool for seismo-acoustic automatic association, *Pure and Applied Geophysics,* **178**, 2437-2458, doi:10.1007/s00024-020-02508-x.
- Myers, S.C., Begnaud, M.L., Ballard, S., Pasyanos, M.E., Phillips, W.S., Ramirez, A.L., Antolik, M.S., Hutchenson, K.D., Dwyer, J.J., Rowe, C.A. and Wagner, G.S., (2010). A crust and upper-mantle model of Eurasia and North Africa for *Pn* travel-time calculation, *Bulletin of the Seismological Society of America,* **100** (2), 640-656, doi: 10.1785/0120090198.
- Nippress, A., and Green, D., (2023). Global empirical models for infrasonic celerity and backazimuth, *Geophysical Journal International,* **235**, 1912-1925, doi:10.1093/gji/ggad334.

Back-up Slides

Maximum *a posteriori* solutions for the Ground Truth Events

Event 1: Beirut, 2020-Aug-04





- MAP locations (circles) are closer to Ground Truth than the mean locations (stars).
- MAP origin times (circles) are earlier than the mean OT (squares).
- Detections are taken from Nippress & Green (2023) and are all to the west of the event:
  - I48TN, Tunisia, 2398 km
  - I26DE, Germany, 2450 km
  - I17CI, Ivory Coast, 5129 km
  - I42PT, Azores, 5606 km

Event 2: Sayarim, 2011-Jan-26

- MAP locations (circles) are closer to Ground Truth than the mean locations (stars).
- MAP origin times (circles) are closer to Ground Truth OT than the mean OT (squares).
- Detections are taken from Nippress & Green (2023) and are all to the east of the event:
  - I31KZ, Kazakhstan, 2982 km
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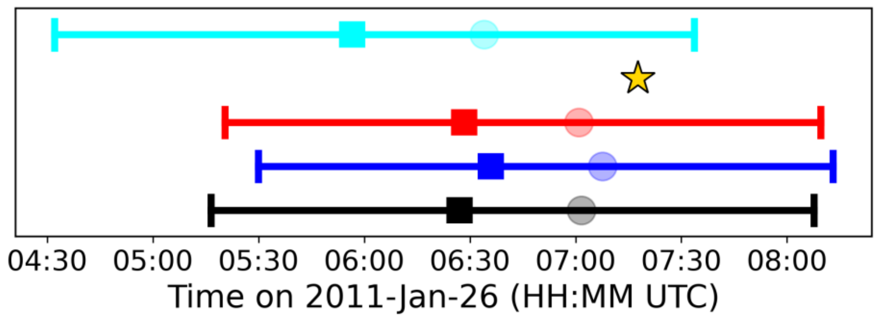
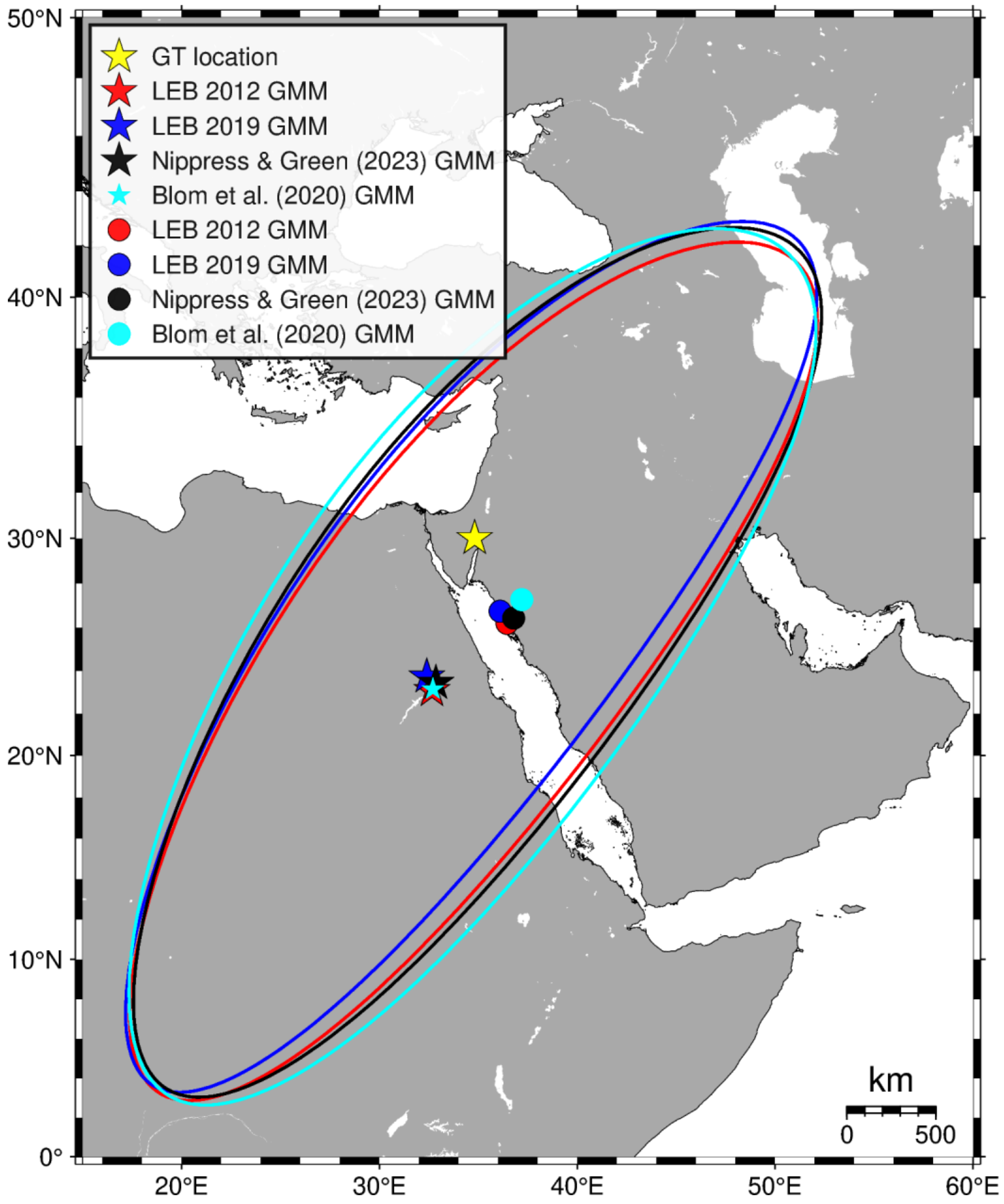
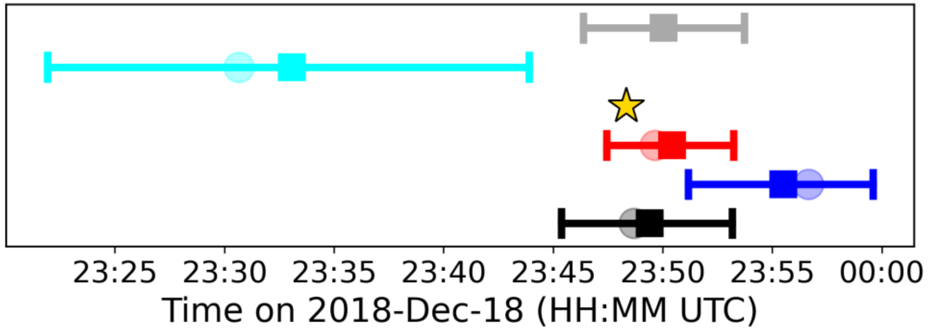
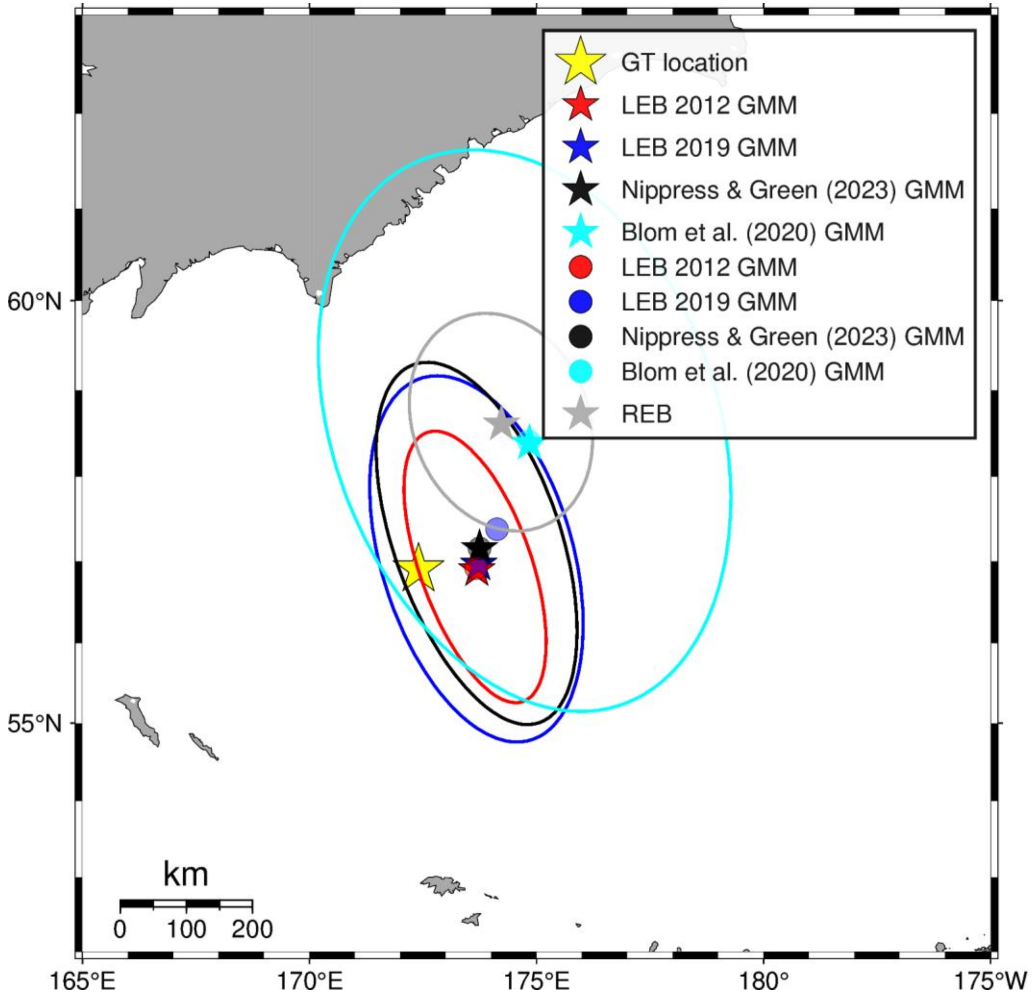




Event 3: Bering bolide, 2018-Dec-18





- MAP locations are comparable to mean locations for 3 of the 4 GMMs
- MAP origin times (circles) are earlier for 3 of the 4 GMMs, moving 2 of the 3 closer to the Ground Truth OT.
- Detections are taken from Grant et al. (2024). There are 11 detections providing good azimuthal coverage: I44RU, I53US, I30JP, I56US, I59US, I46RU, I10CA, I37NO, I43RU and I26DE and observations at distances from ~1000 km to ~8000 km.

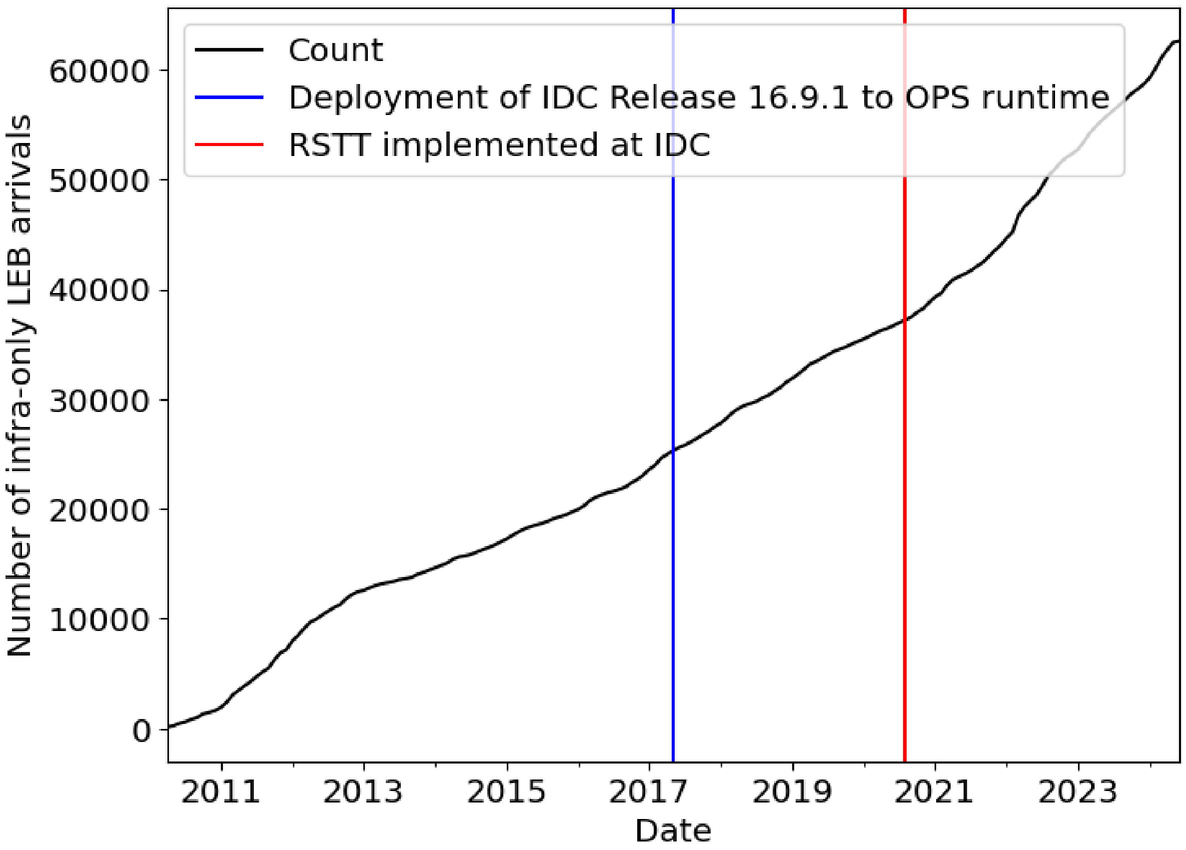
IDC Celerity-range model changes – impact on rate of associated detections? *No clearly observed impact – see following figures.*

2010-2024

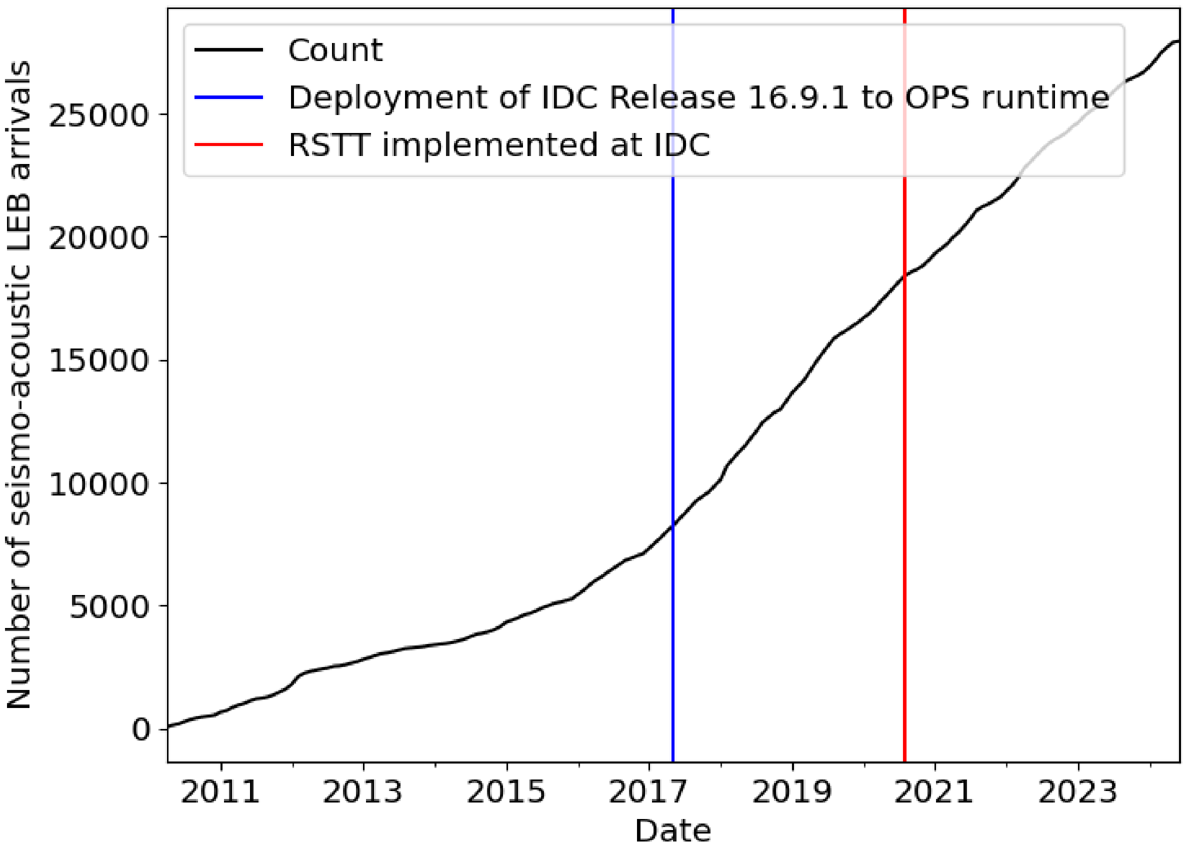
Rate of associated detections - **LEB**

2010-2024

Infrasound-only



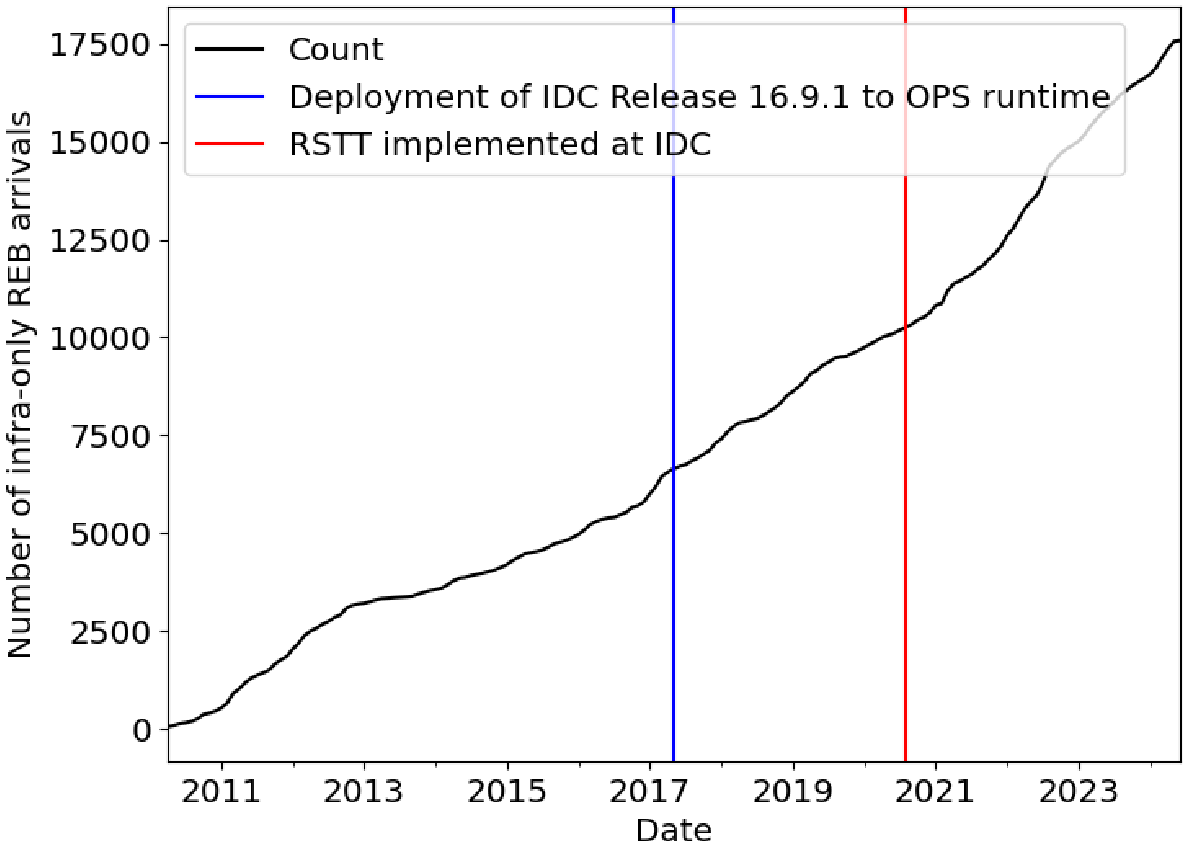
Seismo-acoustic



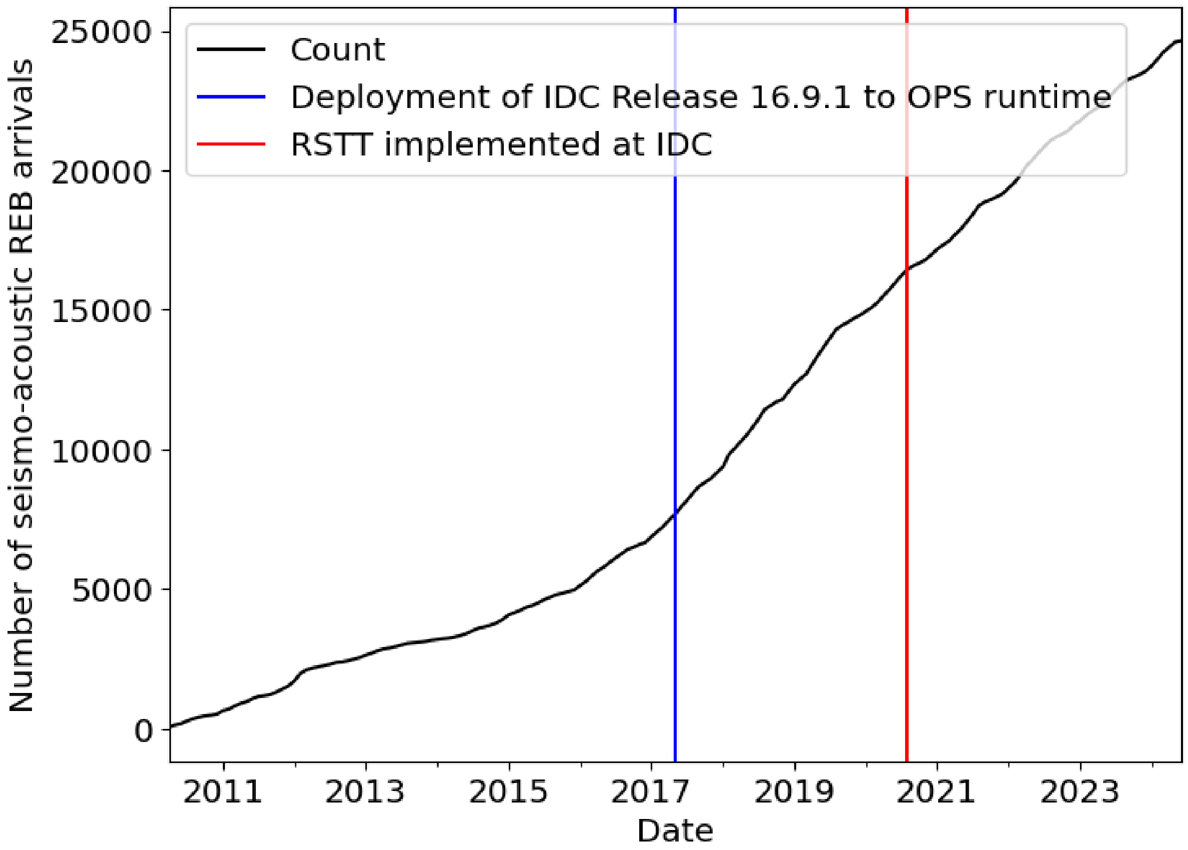
Rate of associated detections - **REB**

2010-2024

Infrasound-only



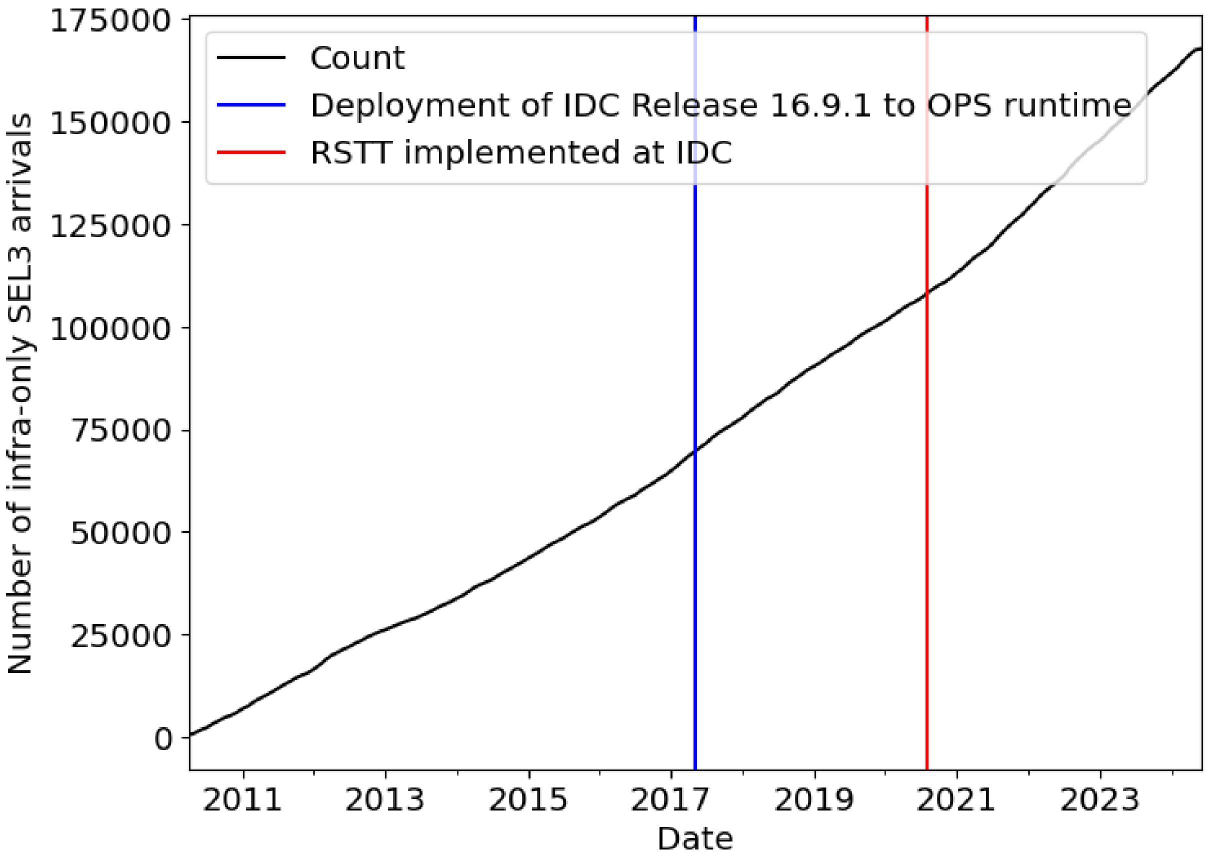
Seismo-acoustic



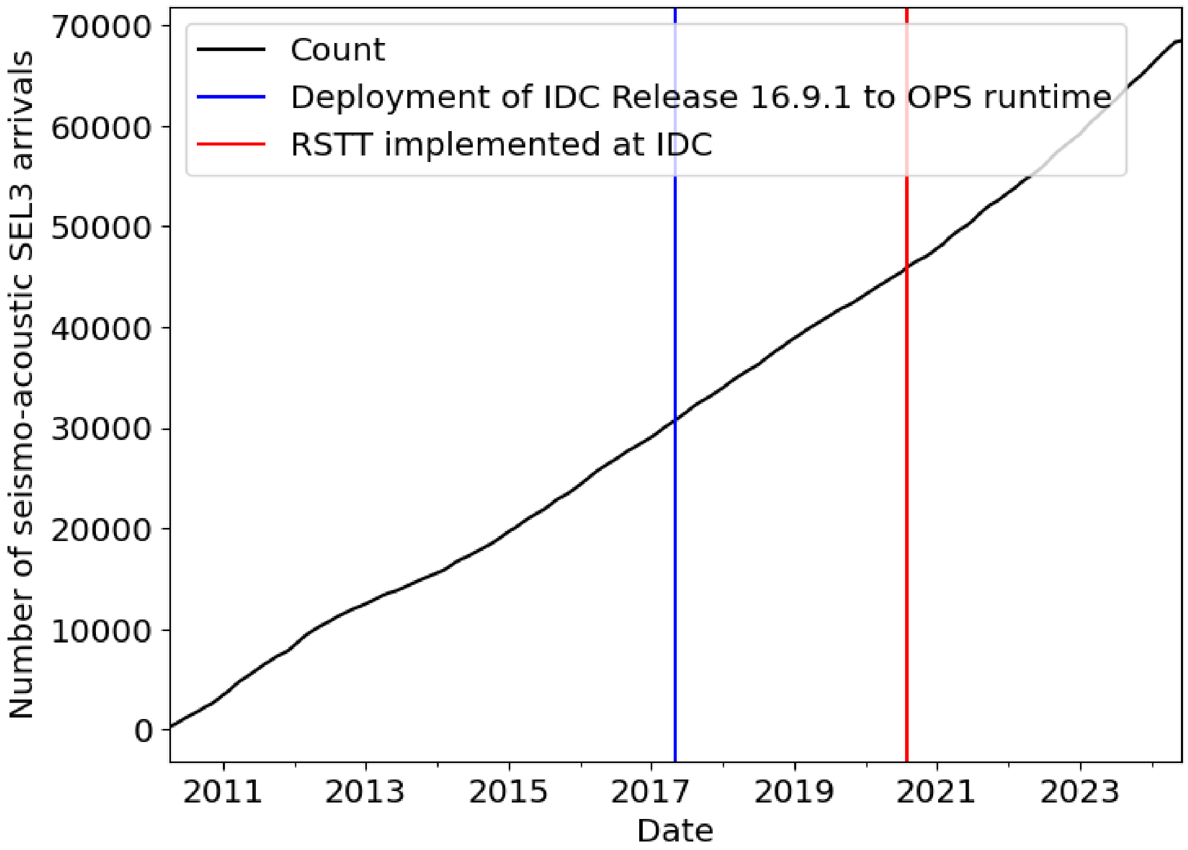
Rate of associated detections – **SEL3**

2010-2024

Infrasound-only



Seismo-acoustic



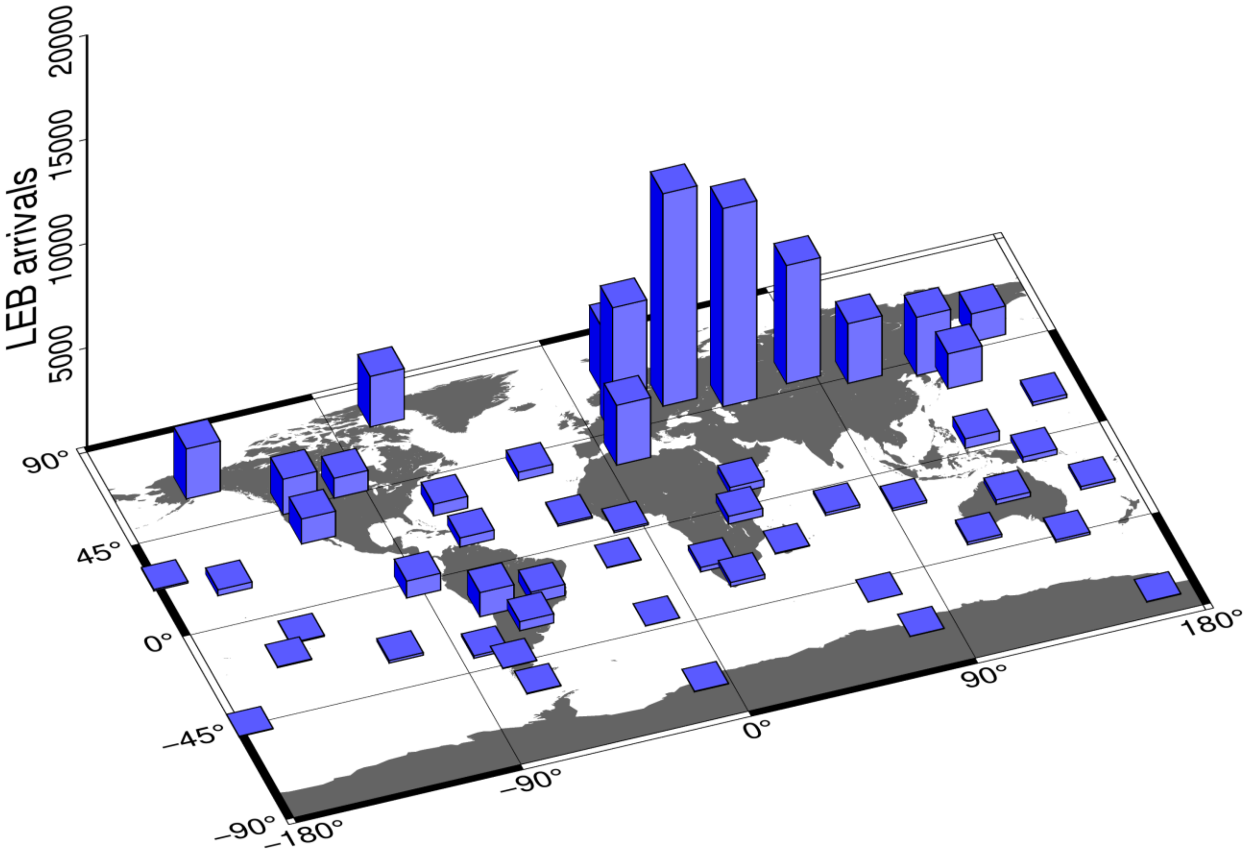
Global distribution of associated detections – *has not changed significantly since a previous review of 5 years of data 2010-2015 see: Green and Nippress (2015) Five Years of Infrasound Arrivals in the International Data Center Bulletins: A Review, presented at ITW2015, Vienna.*

2010-2024

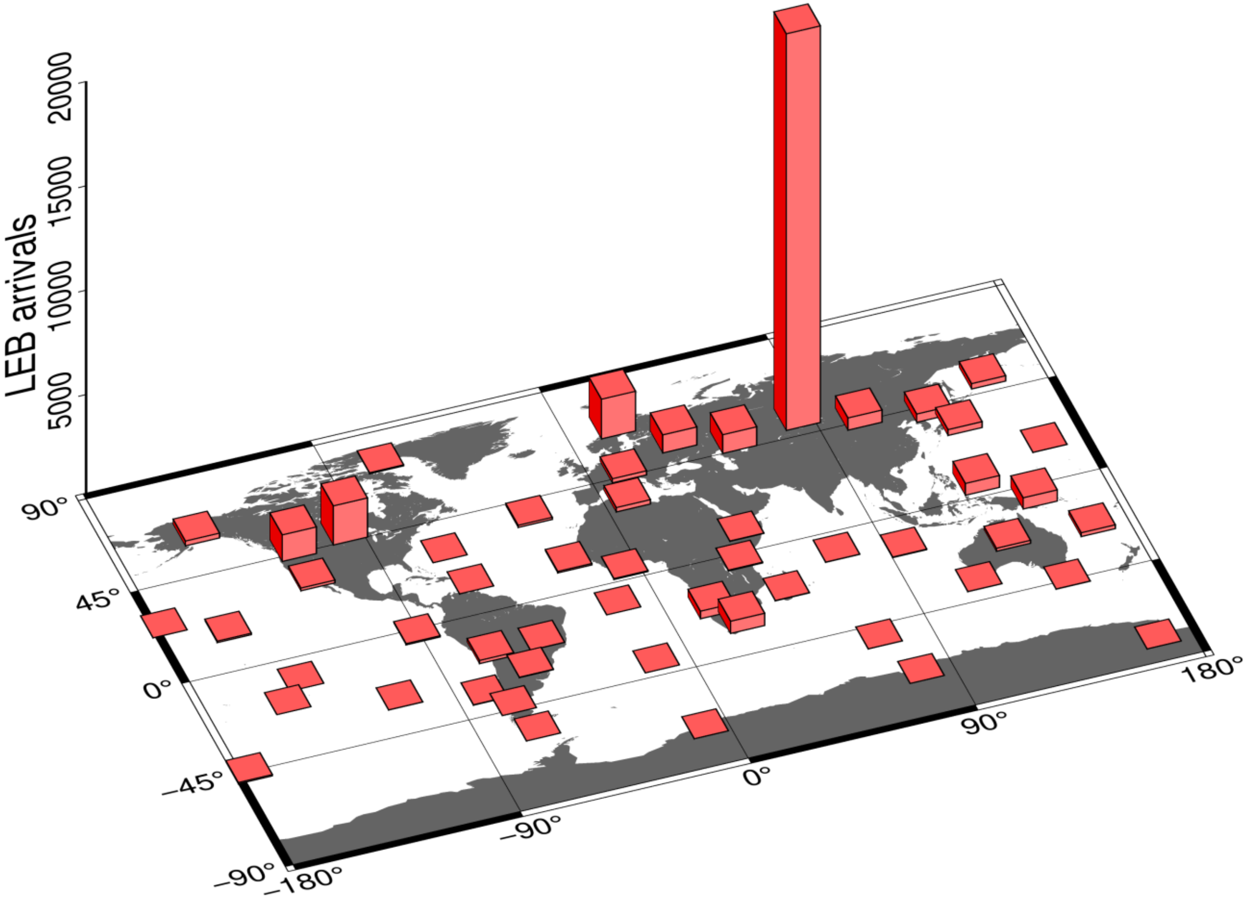
Global distribution of associated detections - **LEB**

2010-2024

Infrasound-only



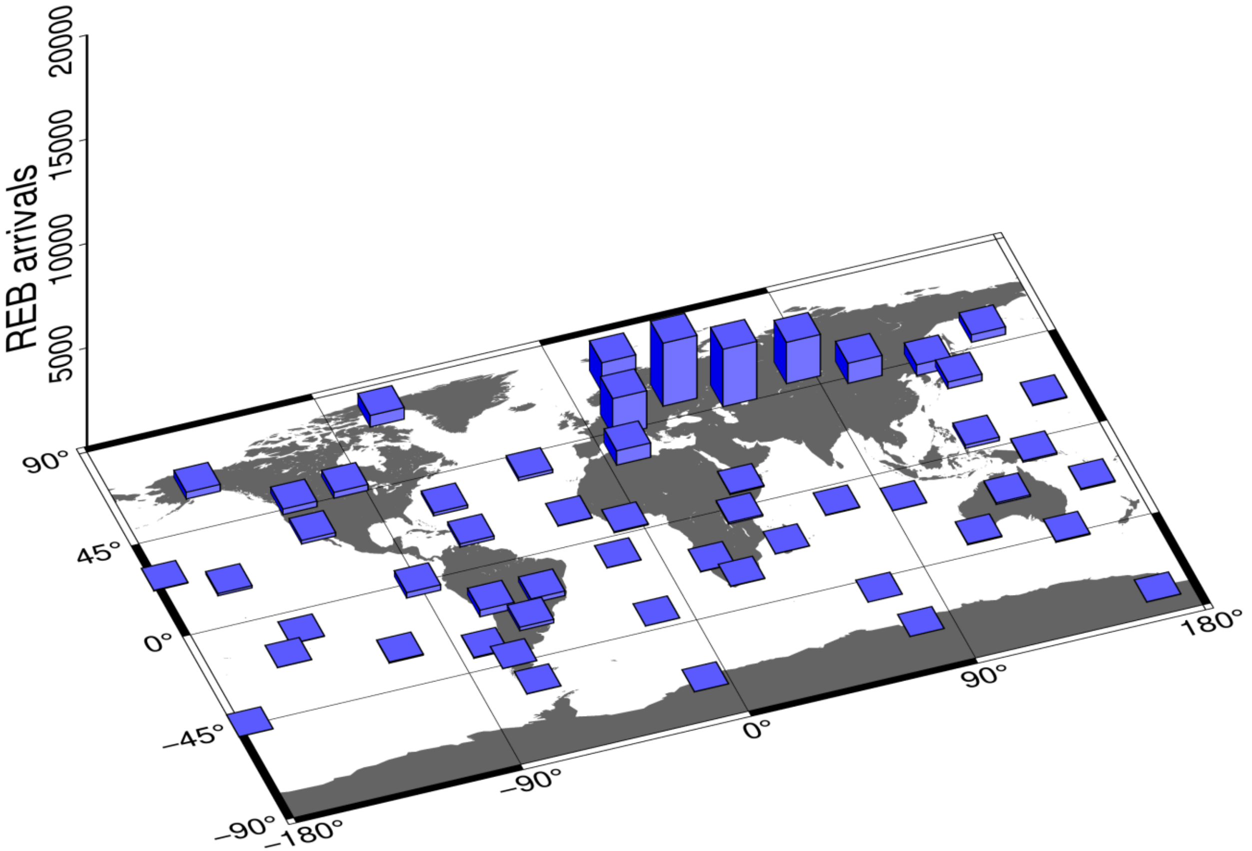
Seismo-acoustic



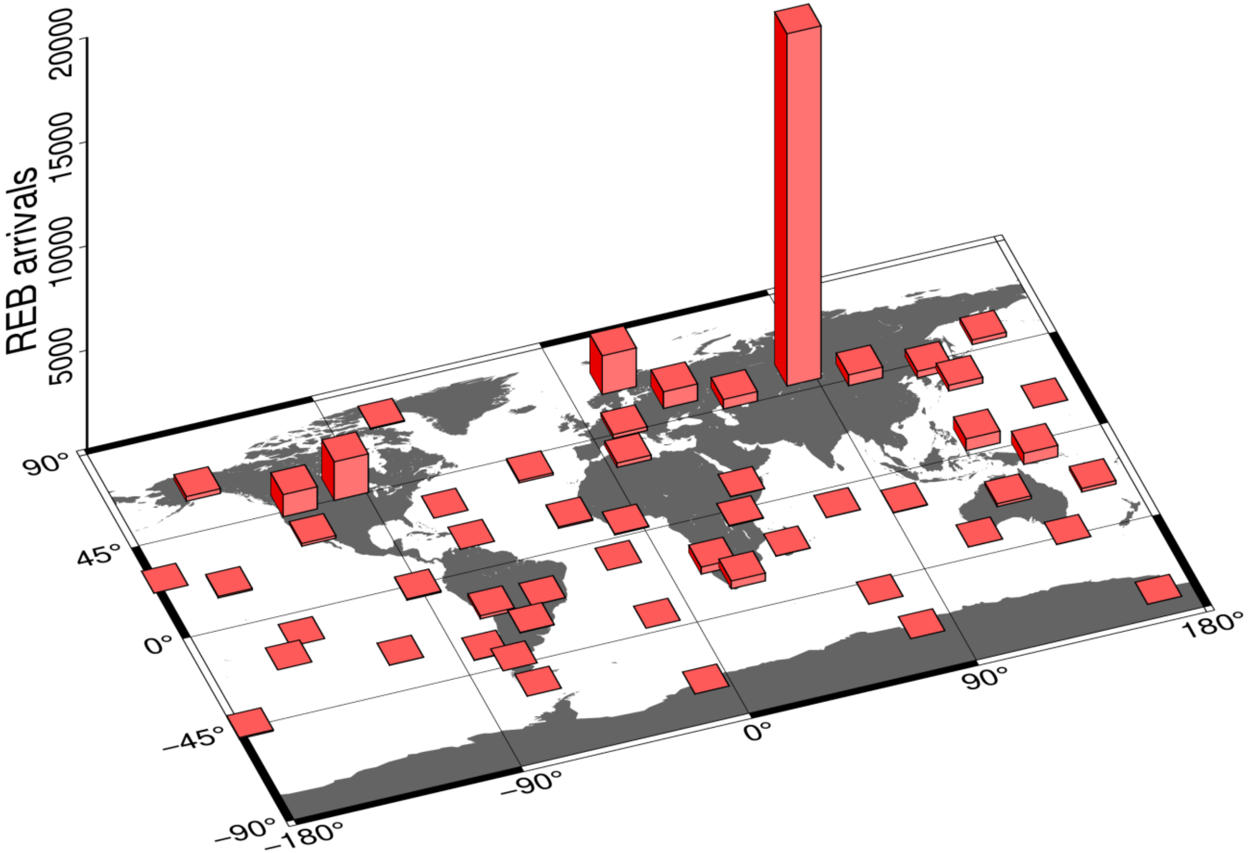
Global distribution of associated detections - **REB**

2010-2024

Infrasound-only



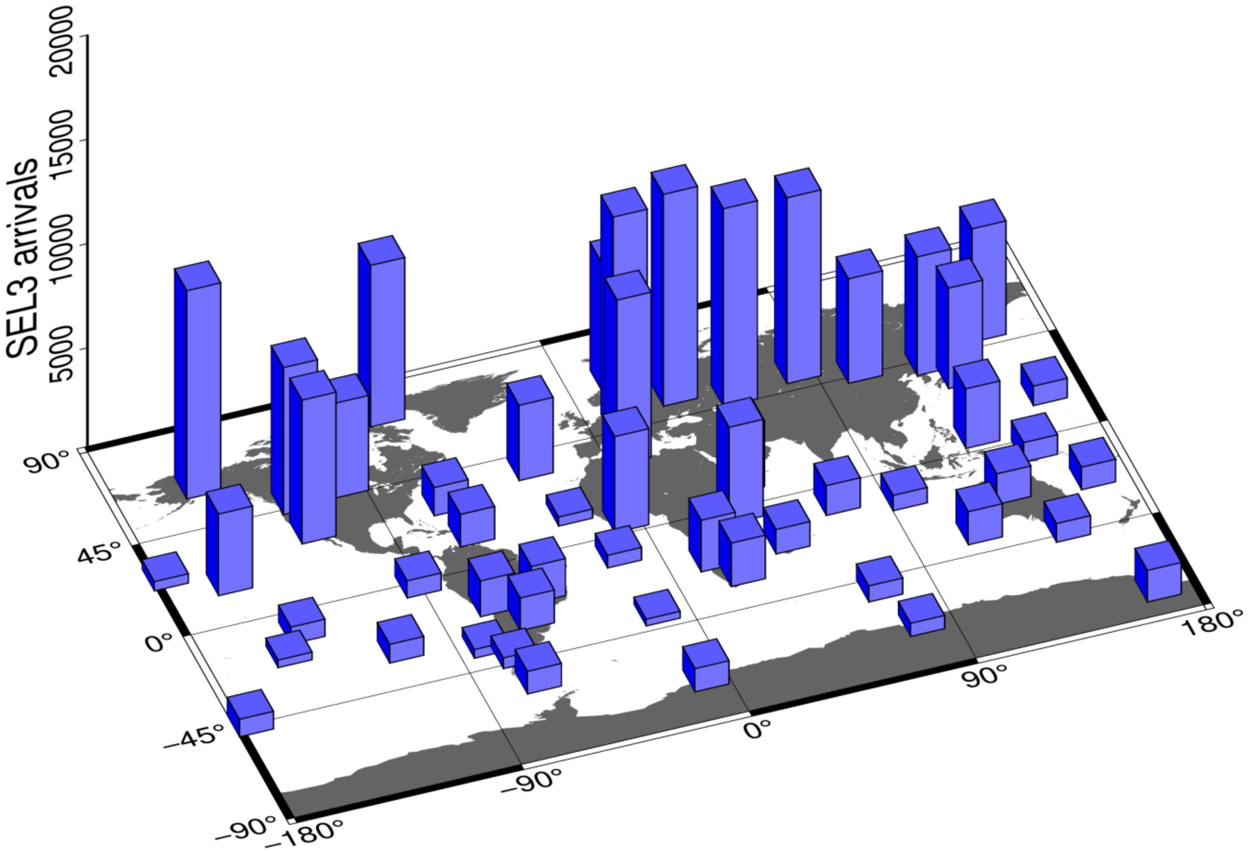
Seismo-acoustic



Global distribution of associated detections – **SEL3**

2010-2024

Infrasound-only



Seismo-acoustic