P1.1-672: Unusual infrasound observations from the August 2020 Beirut explosion

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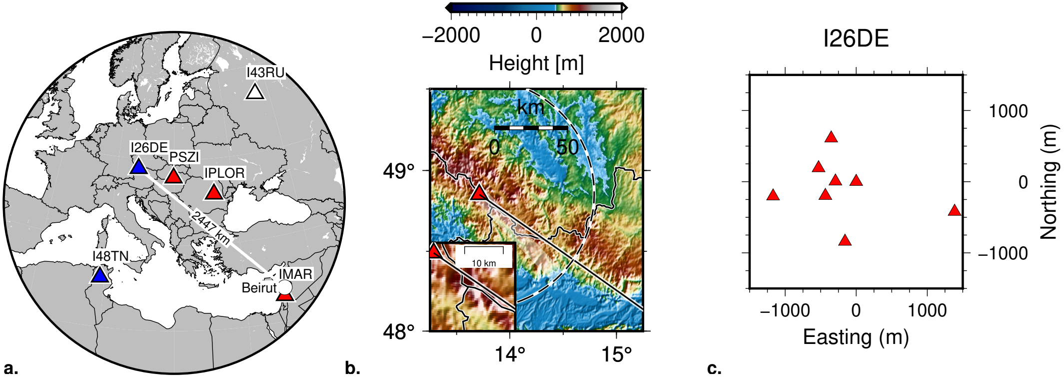
Background

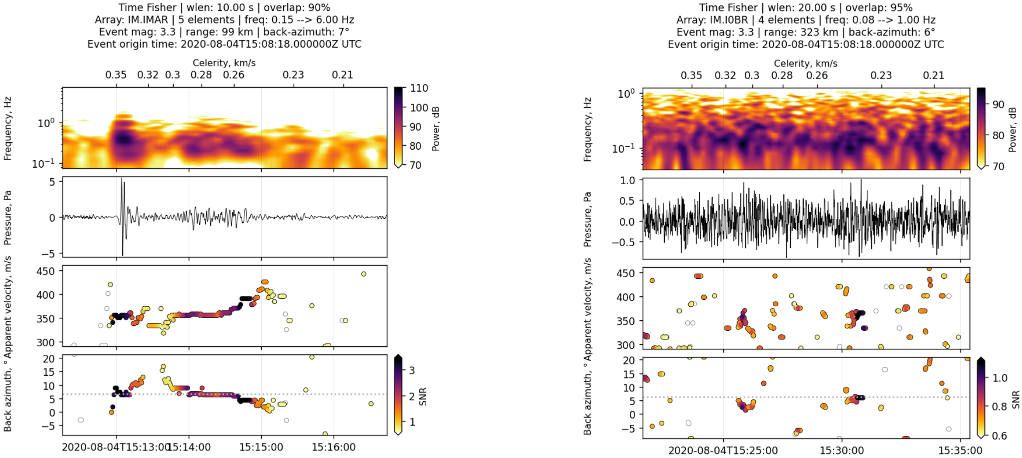
- A warehouse of ammonium nitrite exploded on 4 August 2020, leading to loss of life and property
  - One of the most powerful artificial non-nuclear explosions in history
- Blast wave was widely felt and heard
  - Audible as far as Cyprus (240 km)
  - Acoustic arrivals detected on seismometers
  - USGS seismic event with m_L 3.3
- Seismo-acoustic source has been characterized elsewhere
  - Pilger et al., Sci. Rep. (under review)
  - Yield estimate 0.5-1.1 kT TNT eq.
  - InSAR derived damage maps

Infrasonic detection over the Euro-Mediterranean region



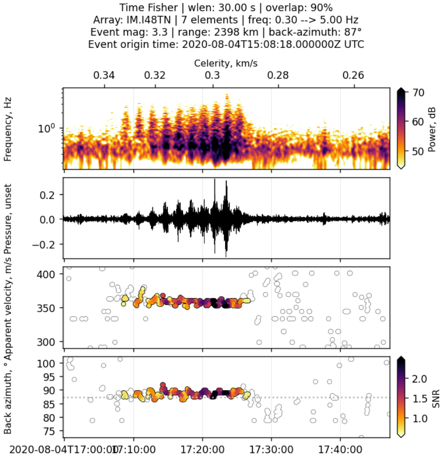
- Infrasound detections on I17CI (Ivory Coast, 5129 km), I42PT (Azores, 5605 km) and I11CV (Cape Verde, 6206 km)
- This presentation: focus on propagation towards IMAR / I26DE / I48TN / PSZI / IPLOR
- Signals on distant arrays show characteristics that are unusual of long-range summertime propagation conditions

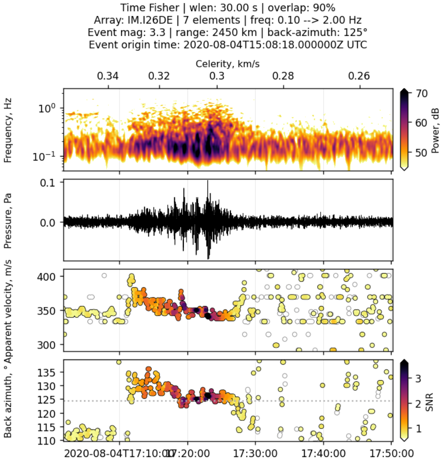
Observations in Israel



- IMAR (100 km): direct wave, followed by reflections from middle atmospheric layers
- Dimona (I0BR) (323 km): Stratospheric and thermospheric refractions buried in the noise

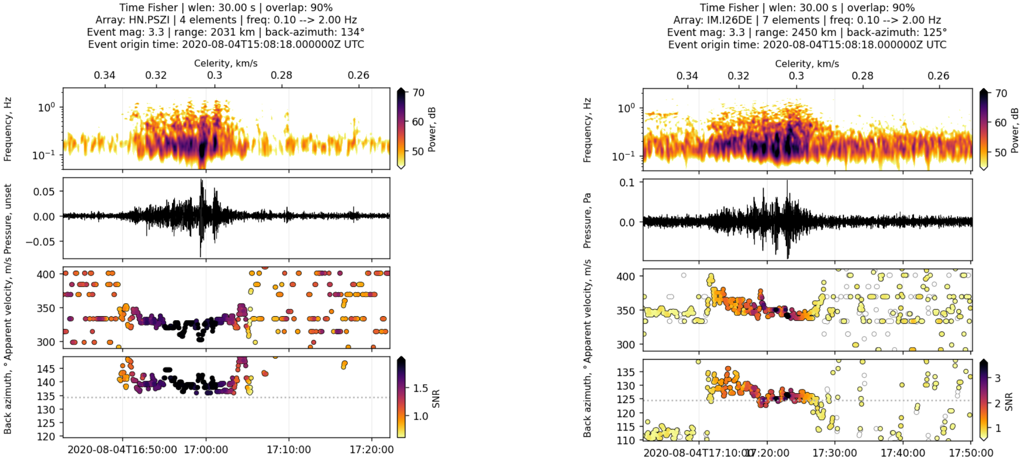
Comparison between two arrays at 2400 km





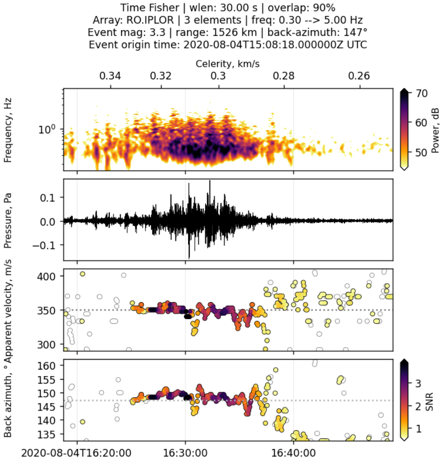
- Signals with tropospheric celerities were observed at I48TN (Tunisia) and I26DE (S Germany)
- The fastest arrivals at IS26 and PSZI appear to have significant back azimuthal scatter
- At I26DE (and PSZI) curious trace velocity trends are observed, from high to low

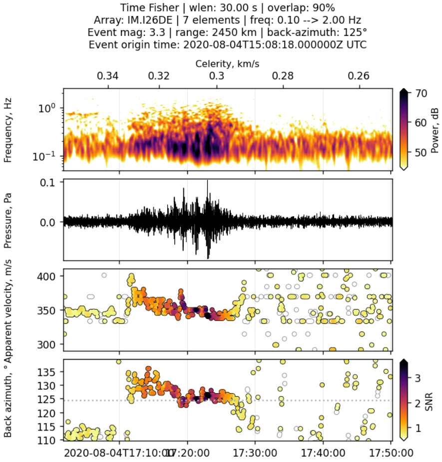
Comparison PSZI and I26DE



- Signals with tropospheric celerities were observed at PSZI (Hungary) and I26DE (S Germany)
- The fastest arrivals at IS26 and PSZI appear to have significant back azimuthal scatter
- At I26DE (and PSZI) curious trace velocity trends are observed, from high to low

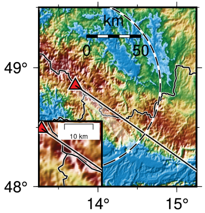
Comparison IPLOR and I26DE

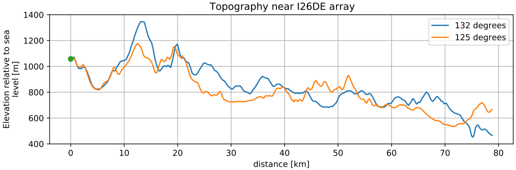


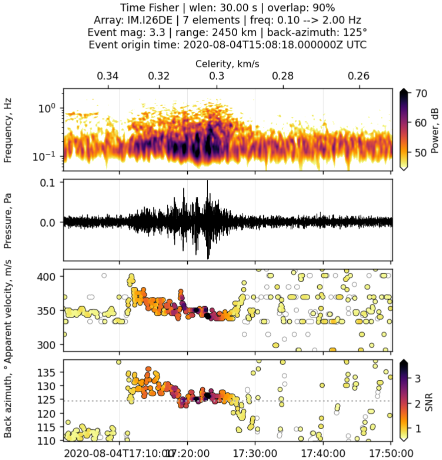


- Signals with tropospheric celerities were observed at IPLOR (Romania) and I26DE (S Germany)
- Back azimuthal scatter and trace velocity trends not observed at IPLOR

Azimuthal scatter at I26DE and nearby topography

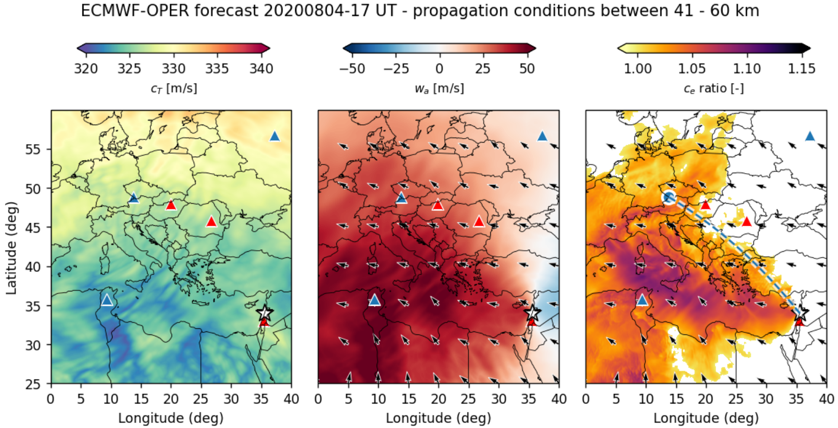






- Scattered azimuths come from a direction with elevated, but not steep terrain
- Tropospheric propagation must have occurred along the source-receiver path
- Unclear how this would influence trace velocity observations

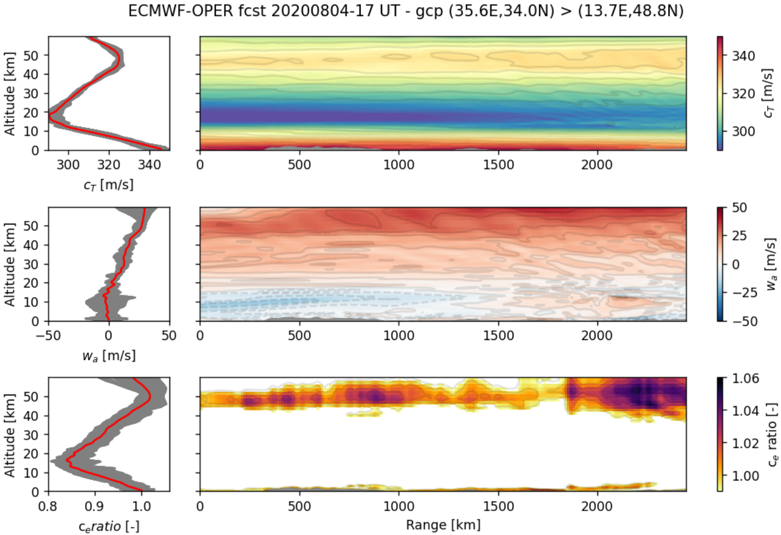
Simulating stratospheric propagation efficiency (40-60 km)



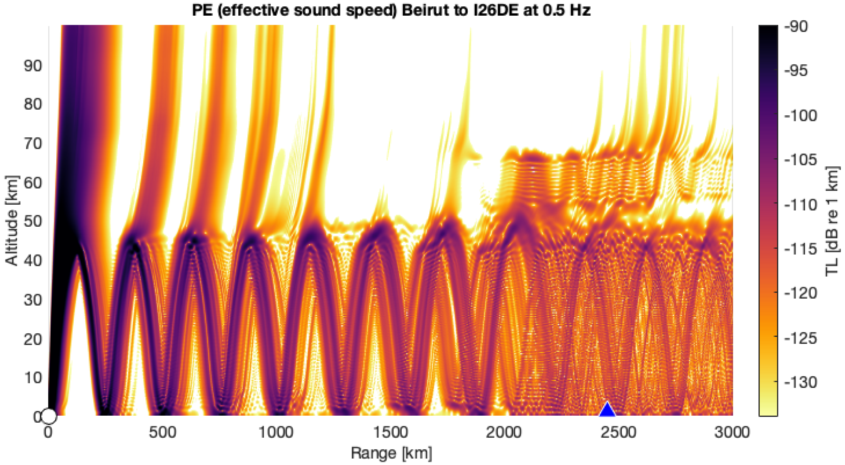
- The atmosphere is - to leading order - a vertically layered medium, with (some) lateral variability
- In-plane propagation sensitive to variations in the effective sound speed ($c_{eff} = c_T + w_a$)
- Ground-to-ground ducting can be approximated by c_e-ratio $c_r(z) = \frac{c_e(z)}{c_e(z{=}z_{gnd})}$

From source to receiver: a vertical transect through the atmosphere

- Stable stratospheric duct around 50 km altitude
- Jetstream appears at mid-latitudes but plays no role in ducting

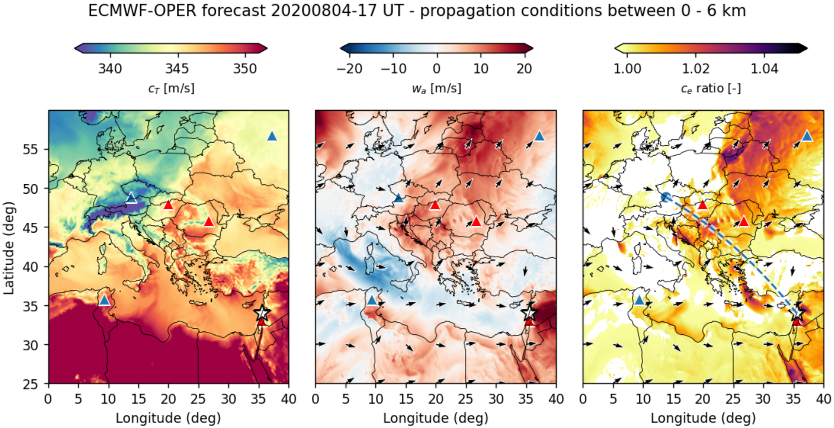


Infrasound propagation modeling using Parabolic Equation method



- Colorscale corresponds to energy loss along propagation path
- Stratospheric waveguide is main duct; some interaction with a weak near-surface duct

Simulating lower tropospheric propagation efficiency (0-4 km)



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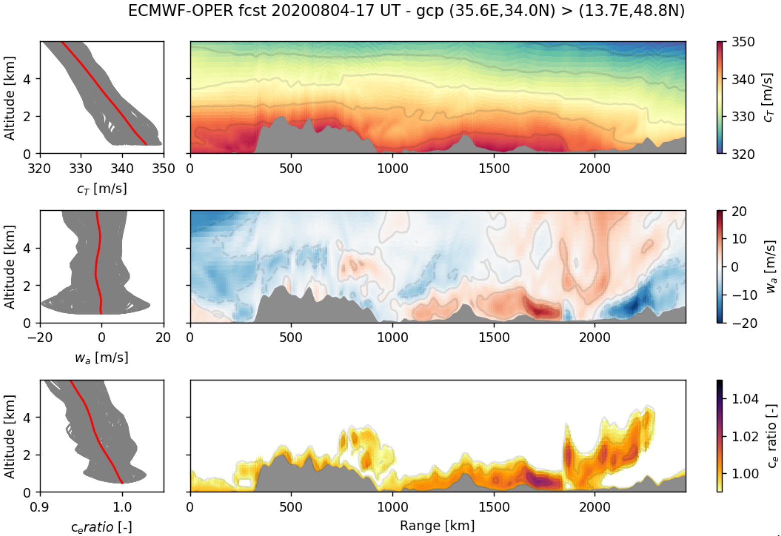
- Ground-to-ground ducting can be approximated by c_e-ratio $c_r(z) = \frac{c_e(z)}{c_e(z=z_{gnd})}$

From source to receiver: a vertical transect through the atmosphere

- Tropospheric generally inefficient over longer ranges
- A partial duct appears beyond 2000 km range
- Forecast skill of ECMWF model is challenged in mountainous terrain

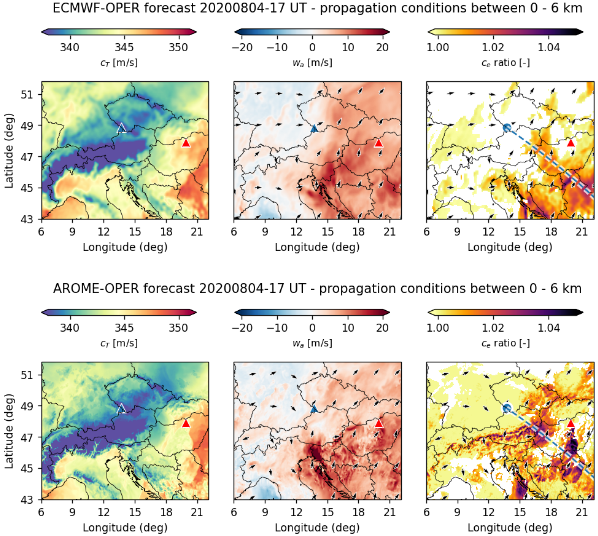


Comparison between ECMWF and the non-hydrostatic AROME model

- AROME model:
  - 2.5 km scale resolution
  - Tropospheric model only
  - Boundary conditions provided by ECMWF
  - Allows to resolve non-hydrostatic motion

- Near-surface propagation conditions differ between AROME and ECMWF models

AROME model data courtesy of Christoph Wittman and Ulrike Mitterbauer (ZAMG)



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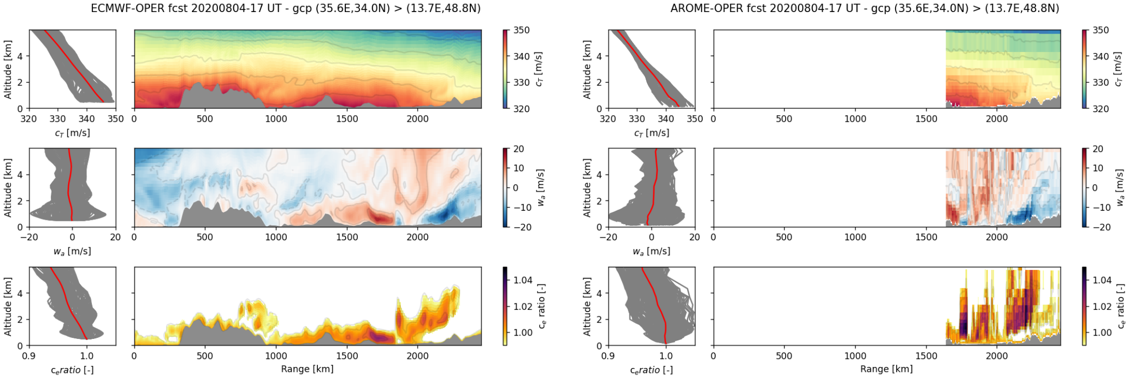

AROME model data courtesy of Christoph Wittman and
Ulrike Mitterbauer (ZAMG)

Conclusions

- The 4 August 2020 Beirut explosion gave rise to both seismic and acoustic arrivals that were detected as far as 6200 km distance.
- Observations at stations in Europe reveal a dispersed wavetrain with anomalous characteristics: (1) tropospheric celerities, (2) scattered back-azimuths and (3) inverse trace velocity trend
- It is hypothesized that the tropospheric phases interacted significantly with topography. This requires the application of full-wave modeling techniques including terrain.