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Yield estimation of the 2020 Beirut explosion using open access waveform and remote sensing data

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ORAL PRESENTATION

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Origin and Aftermath

- huge, accidental explosion in the city of Beirut, Lebanon
- 4th of August 2020 around 18:08 local time (15:08 UTC)
- combustion of approximately **2.75 kt ammonium nitrate** stored in harbor warehouse, followed by huge shock wave

  - thousands of casualties with more than 200 fatalities
  - immense damage to buildings and infrastructure

- local authorities conducted on-site investigations
- limited access to the explosion site due to various reasons

  - destruction, contamination, SARS-CoV-2 pandemic
  - sparse direct information and data from the explosion

- **Independent**, third-party estimation of the yield of the explosion from the analysis of **publicly available** waveform and remote sensing data

Source: Planet Labs Inc.

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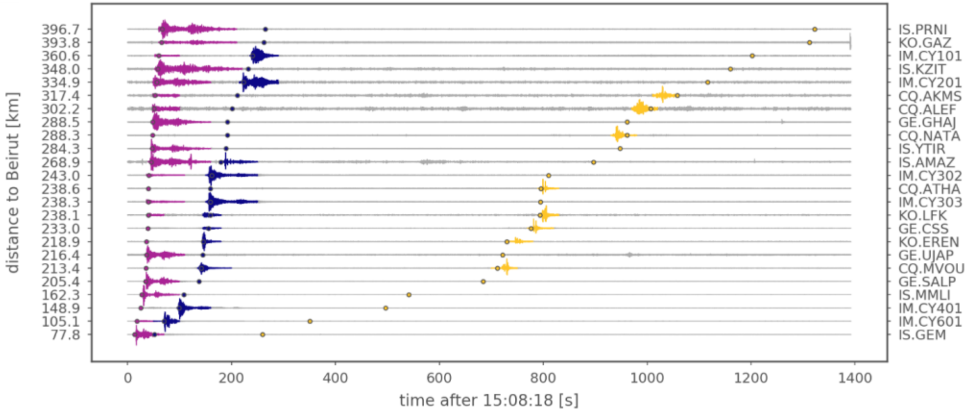
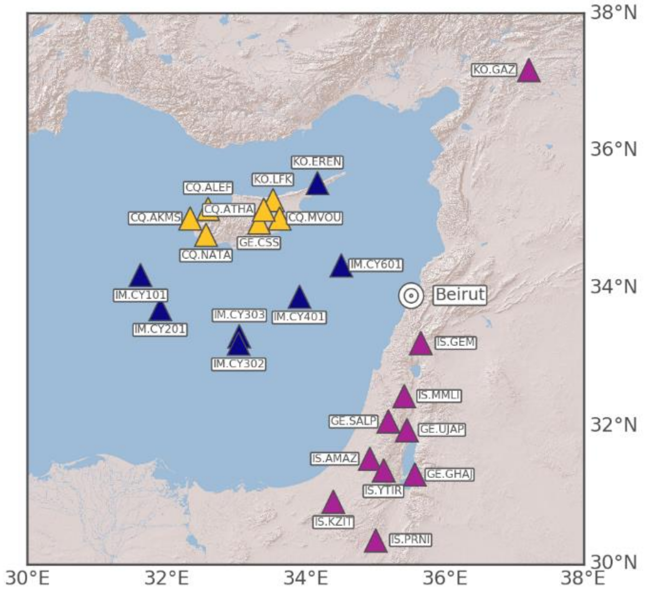
Publicly available data from seismometers

- seismometers located in the region around Beirut (data available from GEOFON/IRIS networks)
- signals detected by at least 24 seismometers in distances of up to 400 km
- identification of seismic, hydroacoustic and infrasonic phases
  - seismic phases: onshore north and south of Beirut
  - hydroacoustic: at ocean bottom seismometers
  - infrasonic phases: seismometers located on Cyprus





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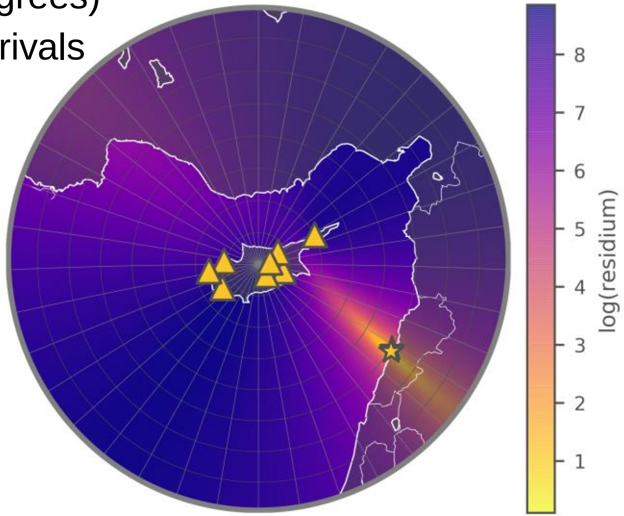
Localization using the acoustic arrivals on Cyprus

- grid search method (distances up to 400 km, backazimuth up to 360 degrees)
- linear regression analysis to fit apparent velocity to observed seismic arrivals
  - ➢ best fitting apparent velocity: 0.344 km/s
  - ➢ best source location: 33.863°N, 35.502°E
  - ➢ origin time: 15:08:18 UTC



Yield estimation using seismic data

- **moment tensor inversion** using local seismometer stations
  - ➢ moment magnitude: 3.47, **estimated yield: 1.08 kt TNT** (using relation of moment magnitude to strain energy drop via shear stress-change/modulus, *Kanamori 1977*)
- relation of **body wave magnitude** measurement to yield (as a lower limit threshold)
  - ➢ body wave magnitude: 3.2 (REB), **estimated yield: 0.13 to 0.34 kt TNT** (using wet hard rock and dry unconsolidated rock assumption for the predominant dolomite rock at explosion site, *Brax et al. 2016*)

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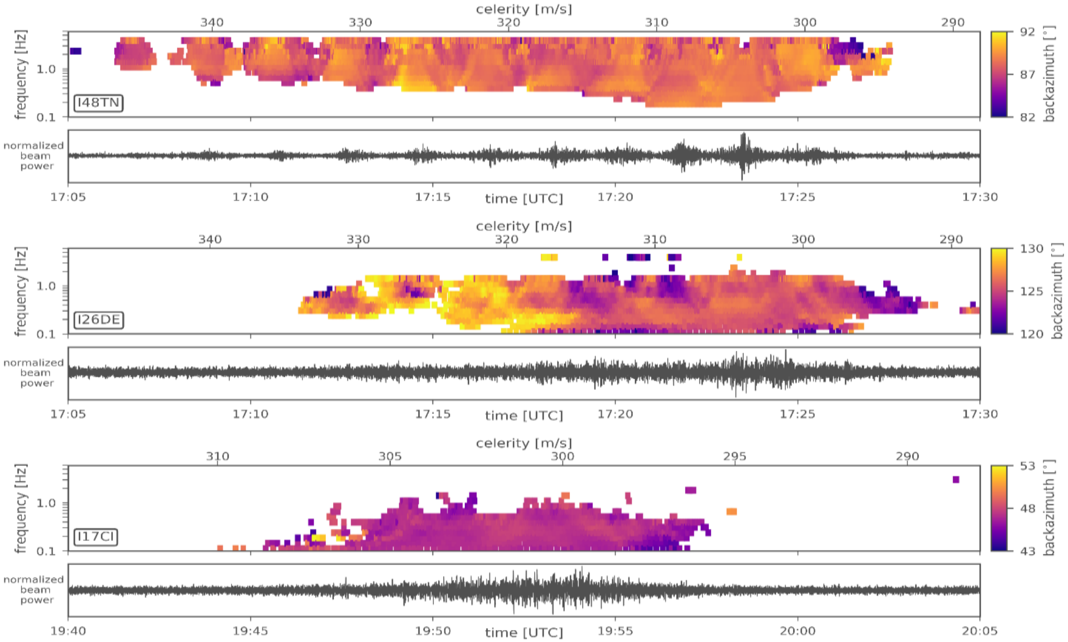
Infrasonic signatures

- IMS infrasound arrays in distances of up to 10000 km from Beirut were investigated
- detections associated with the explosion found at 5 IMS infrasound arrays:
  - **I48TN (Tunisia)**
  - **I26DE (Germany)**
  - **I17CI (Ivory Coast)**
  - I42PT (Azores)
  - I11CV (Cape Verde)



- **PMCC** (progressive multi-channel correlation) **method**

for the determination of:

- backazimuth of the signal for source localization
- amplitude/period of the signal for yield estimation

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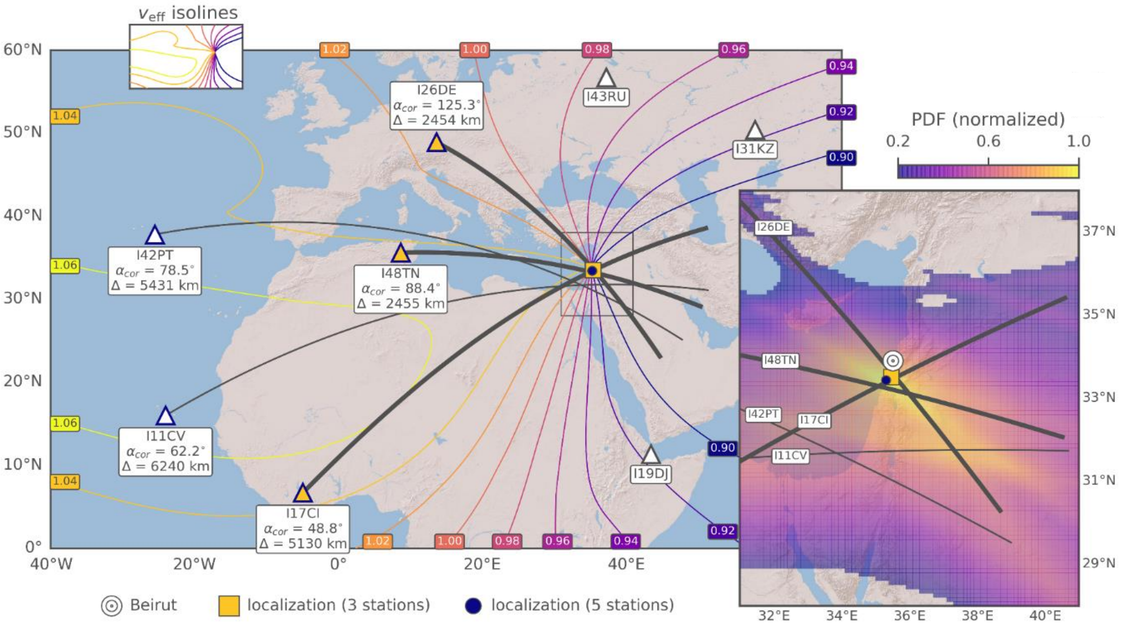
Localization using IMS infrasound arrays

- source localization using a grid-search algorithm
- selection of a station subset of the three best-detecting stations (I26DE, I48TN, I17CI)
- source location around 44 km away from ground truth



Yield estimation using infrasound

- also using three best-detecting stations (I26DE, I48TN, I17CI)
- application of two yield relations (AFTAC: *ReVelle et al. 1997;* LANL*: Whitaker et al. 2003*)

➢ **estimated yield: 0.86 to 1.06 kt TNT**

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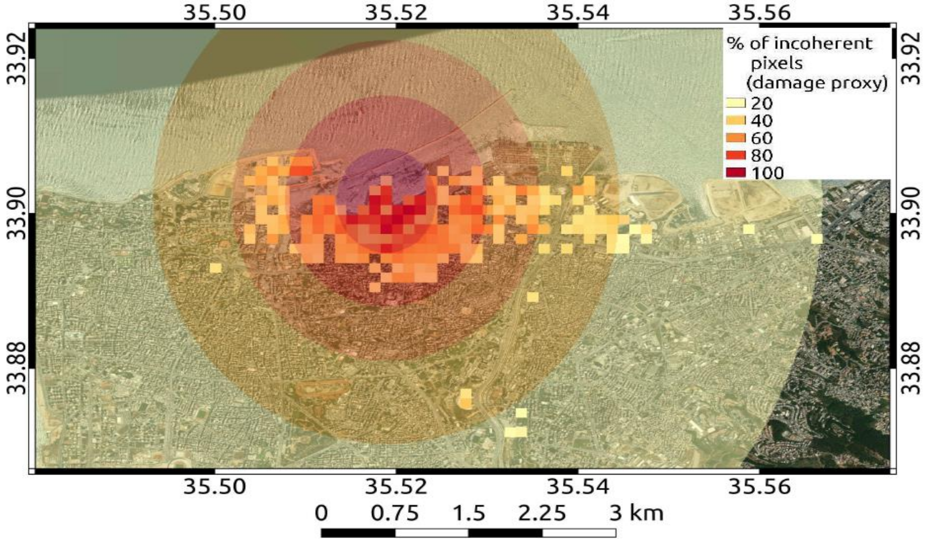
InSAR: Relative and expected damage

- blast of the explosion caused a wide range of damage to buildings
  - ➢ Strong differences in space-borne SAR images before and after the explosion
- quantification of this differences by interferometric coherence, which is related to the relative damage
- Relative damage is measured in percent of pixels that experienced significant loss of interferometric coherence
  - ➢ Comparison of relative damage to expected damage after relative damage classes

Source: ESA

InSAR (Interferometric synthetic-aperture radar) from **Sentinel-1 Satellite**



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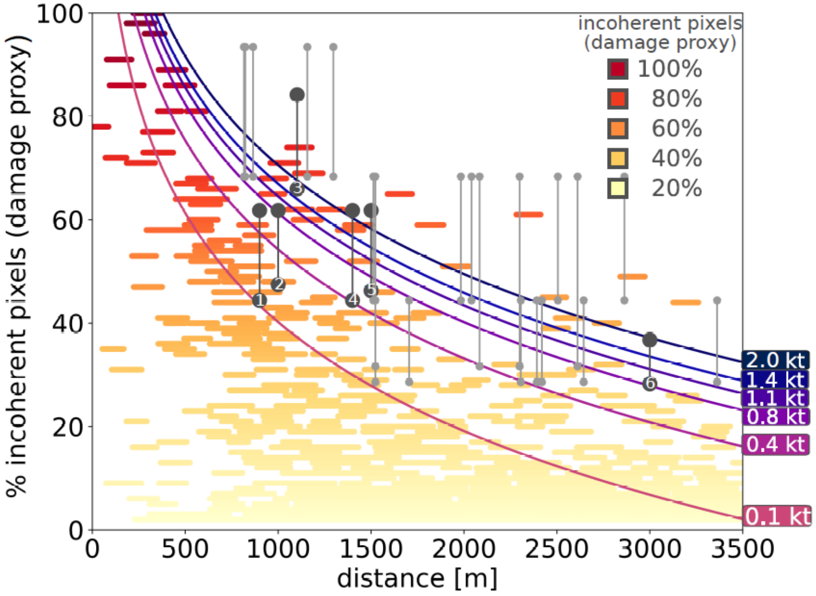
Linking overpressure simulations and InSAR derived damage maps

- “BOOM” equation (*Douglas 1987*) relates yield of an explosion to resulting peak overpressure
- assumption of a relation between peak overpressure and resulting damage

DAMAGE	INCIDENT OVERPRESSURE (kPa)
Typical Glass Window Damage	1.03-1.52
Minor Damage to Some Buildings	3.45-7.60
Panels of Sheet Metal Buckled	7.58-12.41
Failure of Concrete Blockwork	12.41-19.99
Collapse of Wood Framed Buildings	over 34.47
Serious Damage to Steel Framed Buildings	27.58-48.26
Severe Damage to Reinforced Concrete Structures	41.37-62.05
Probable Total Destruction of Most Buildings	68.95-82.74

- 80 kPa overpressure are set to result in 100% destruction
- calibration using ground-truth (media report) information



Yield estimation using InSAR

- Best fitting and upper boundary curves: **estimated yield: 0.8 – 2.0 kt TNT**

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Summary

- Beirut explosion produced **seismic, hydroacoustic and infrasonic waveforms**
- Damage to city infrastructure observable in **InSAR remote sensing** satellite images
- Location accuracy: 44km (IMS-infrasound arrays), < 1km (adding regional seismometers)
- Yield estimation using seismometers, infrasound arrays, InSAR satellite images:
  - ➢ **consistent best yield estimation: 0.8 to 1.1 kt TNT**
  - ➢ good agreement with other published results (*Rigby et al. 2020; Diaz 2021*)
  - ➢ lower (body wave) boundary: 0.13 kt TNT, upper (InSAR) boundary: 2.0 kt TNT
- Utilization of open-access data from seismometers, infrasound arrays, satellites
  - ➢ involves CTBT-IMS sensors as well as **additional national technical means**
  - ➢ allows reliable identification, localization and characterization of the explosion
  - ➢ fulfills the **IMS design goal** to detect any **explosion with a yield around 1kt TNT**

➔ *Also see preprint here:* https://doi.org/10.31223/X5W027