SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

CTBTO
PREPARATORY COMMISSION

CHARACTERIZATION OF THE 4 AUGUST 2020 BEIRUT EXPLOSION FROM THE INFRASOUND COMPONENT OF THE IMS NETWORK

J. VERGOZ[1], C. MILLET[1], Y. CANO[1]

Poster No. P1.1-401

[1]CEA/DAM/DIF, F-91297, Arpajon, France

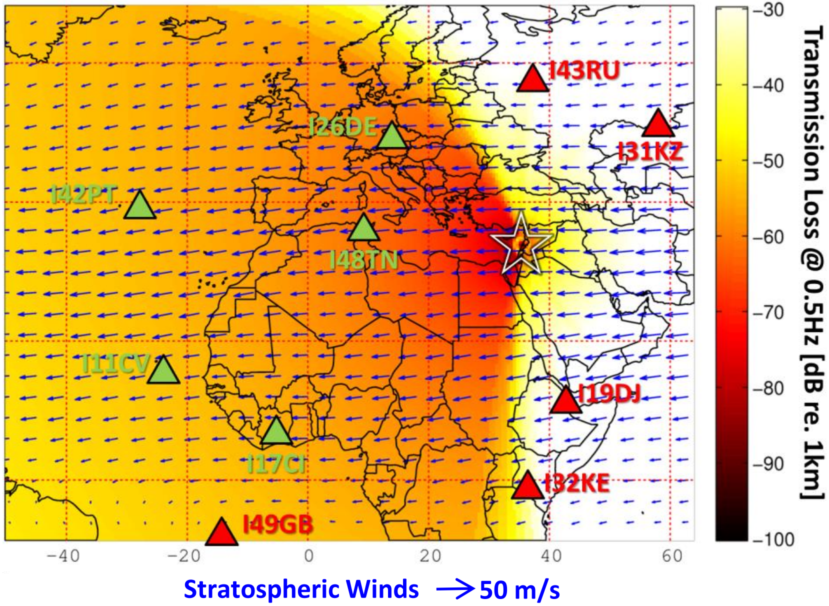
POSTER

INTRODUCTION

- **On August 4, 2020 at 15:08:18 UTC, a warehouse located in the harbor of Beirut heavily exploded**, causing **fatalities** and destroying an entire district of the Lebanese capital
- This explosion is the **most powerful ground-truth event (GT0) of these past years**. It generated SHI arrivals detected in the Euro-Mediterranean region and in Africa
  - As predicted, **infrasound arrivals are detected to the west of the event** (westwards stratospheric jet in August) up to **I11CV** (**6200 km**)
    - → **5 stations of the IMS Infrasound network** : **I48TN, I26DE, I42PT, I17CI, I11CV**
    - → At least **3 national stations** : **IMAR** (Israel), **IPLOR** (Romania), **PSZI** (Hungary)
  - **Tens of regional seismic stations** (M_L 3.3), up to YTIR (265 km)
  - **Hydroacoustic high amplitude T-waves arrivals** on an OBS seismic network (CY60* deployed south of Cyprus) at 100 km

This presentation focuses on localization and energy estimations obtained from IMS infrasound stations only. Special focus is given to I48TN (Tunisia, closest IMS station at 2400 km)

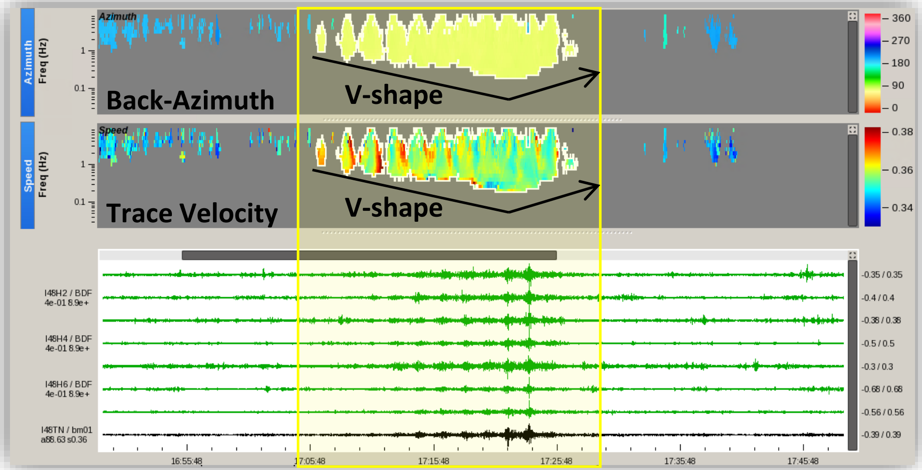
Transmission Loss Map @ 0.5Hz (from Le Pichon's law, 2012)



DATA ANALYSIS
ARRAY PROCESSING WITH DTK-GPMCC (1/2)

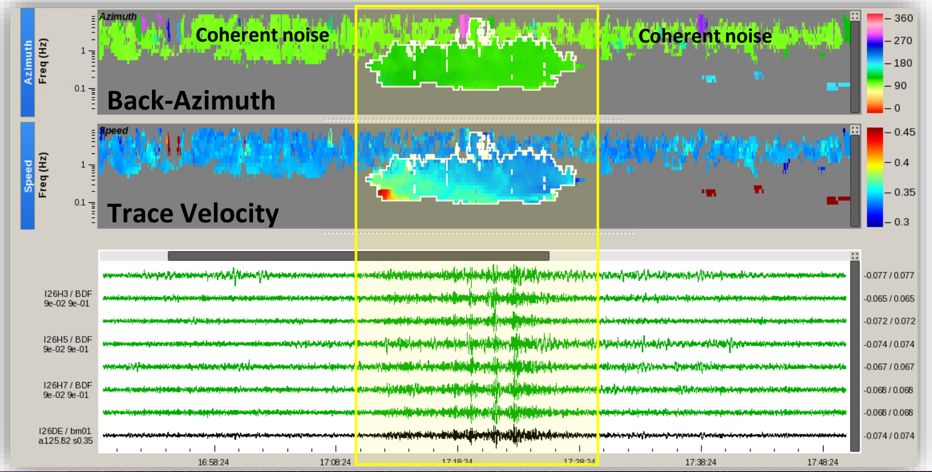
I48TN - 2400 KM

- **11 separated stratospheric arrivals (22 minutes of coherent signal)**
- **Moderate uncoherent wind noise** (2 to 4 m/s at I48H1)
  - → Low frequency content < 0.2Hz is burried in incoherent noise)
- Clear **« V-shape » detection pattern** in time-frequency space
- **Trace Velocity decreases over time**
- First arrivals have **« fast » celerities** for stratospheric arrivals (337m/s)



I26DE – 2450 KM

- **More emergent signal (3 visible stratospheric arrivals, 18 minutes of coherent signal)**
- **Low to Moderate uncoherent wind** noise (1 to 2 m/s at I26H1)
  - → Low frequency content < 0.09 Hz is burried in incoherent noise)
- High frequency content **is burried in coherent noise** (light green detections)
- **Trace Velocity decreases over time**
- First arrivals have **« fast » celerities** for stratospheric arrivals (332m/s)

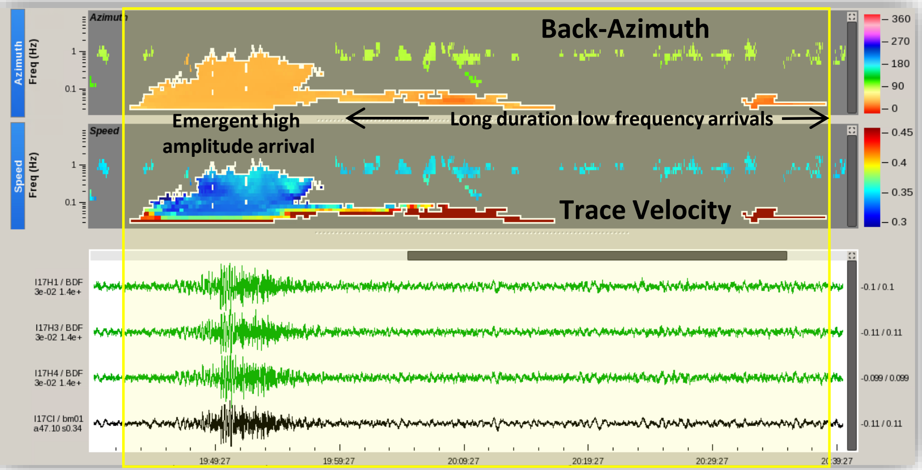


SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P1.1-401

DATA ANALYSIS
ARRAY PROCESSING WITH DTK-GPMCC (2/2)

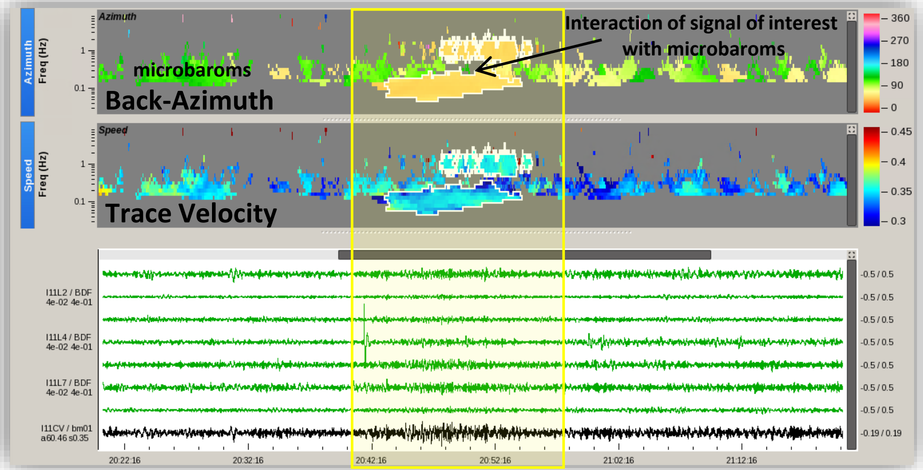
I17CI – 5120 KM

- **One emergent high amplitude stratospheric arrival (10 minutes)**
- **Followed by long duration low SNR / low frequency arrivals (<1 Hz)** refracted from middle and lower thermosphere atmospheric layers (40 min)
- **Very low uncoherent wind noise** (<0.5 m/s at I17H1)
  → **Low frequency content detected down to 0.05Hz**
- **No high frequency content** (>1.5Hz) : High frequencies are too attenuated
- **High amplitude arrivals have stable trace velocities (340-345 m/s)**



I11CV – 6200 KM

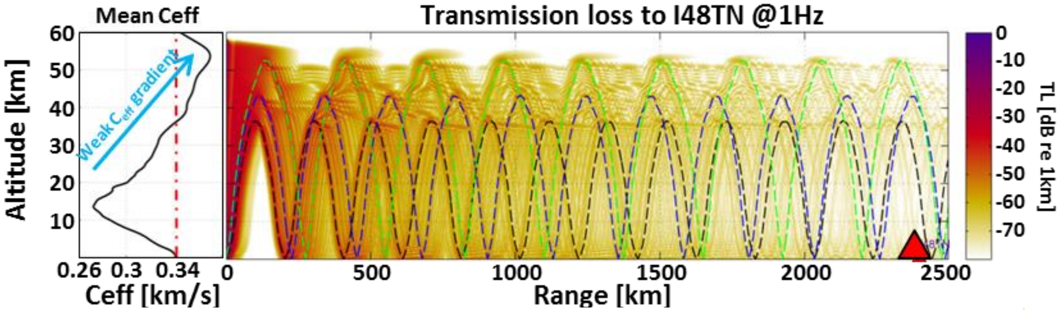
- **One emergent low amplitude stratospheric arrival (10 minutes)**
- **Low uncoherent wind noise** (<1.5 m/s at I11L1)
- **No high frequency content** (>1.5Hz) : High frequencies are too attenuated
- **Interaction of signal of interest with microbaroms** in [0.2 Hz – 0.5 Hz] frequency band (coherence loss)

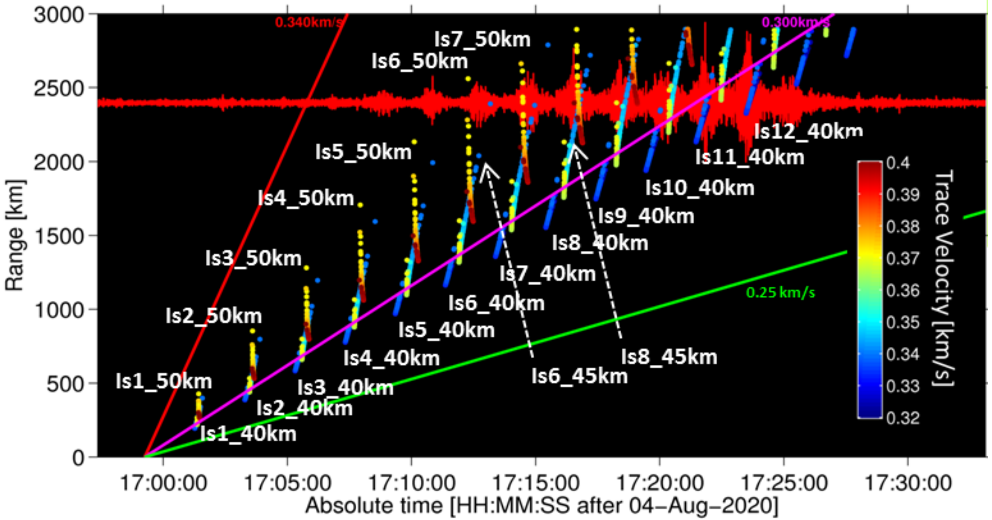


INTERPRETATION OF I48TN DETECTION PATTERN (1/2)

TRACE VELOCITY DECREASE OVER TIME

- **At I48TN and I26DE, trace velocity decreases over time**
  Other well-documented comparable examples :
  - **From ground explosions**: I48TN for 26 August 2009 Sayarim 1 infrasound calibration experiment (~100t TNT eq., comparable ducting conditions)
  - **From bolides**: when fragmentation occurs at low effective sound speed altitudes (eg: Voroneh bolide, 21 June 2018, ~2.8 kt TNT eq., I26DE)
- **When effective sound speed positive gradient is weak in the stratosphere, higher incidence angles which travel on longer paths but in faster velocity layers arrive before lower incidence angles (high trace velocity phases arrive before low trace velocity phases)**
  - **Top right figure**: green ray which refracts at 52 km arrive before black ray which refracts at 37km, even if it travelled a longer path
  - **In summer, C_{eff} weak positive gradients are common**, because altitude of maximum temperature (45-50 km) occurs at lower altitudes than stratospheric jet (55-60 km) -> « thick » effective sound speed duct
  - **In winter, C_{eff} gradients are generally much stronger**. For ground to ground propagation, higher velocity layers in which travel high launch angles do not compensate the longer path. In that case, high trace velocity phases arrive after low trace velocity phases
- **Bottom right figure: Phase identification (from simulated trace velocities simulated with ray tracing and mesured trace velocity values). First arrivals have refracted around 50 km and last arrivals have refracted under 40 km**





SnT 2021

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Poster No.: P1.1-401

INTERPRETATION OF I48TN DETECTION PATTERN (2/2)

THE “V-SHAPE”

- **Broadband full-wave modeling is performed** with FLOWS (normal mode code developped at CEA [Millet, 2016])
  - **Frequency band** : [0 Hz – 1.2 Hz]
  - **Source at 1 km**: blast wave, W=500t TNT eq.
    - → Source parameters from Kinney and Graham, 1985 / Pressure signature from Reed, 1977
  - **Propagation: ECMWF 137 levels 2020/08/05@00:00 UTC** + One realization of **gravity wave** from Gardner Spectrum [Gardner, 1993]
- **One synthetics signal is calculated for each array element** of I48TN (7 elements)
- **Array processing is performed from calculated synthetics with DTK-GPMCC** (same configuration as the one used to process data)

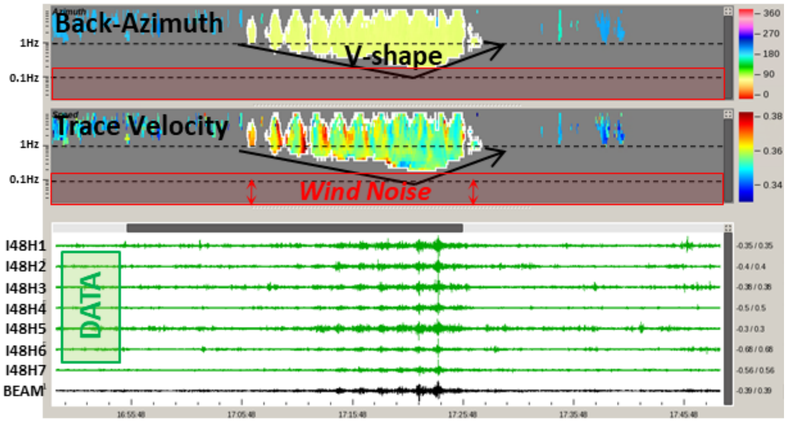
The lack of detections below 0.2 Hz in the data is due to the incoherent wind noise level which is higher than the level of signal of interest

Decrease of trace velocity over time and the fast celerities of first arrivals (337 m/s) are well restored by simulation. These observations are **propagation effects**

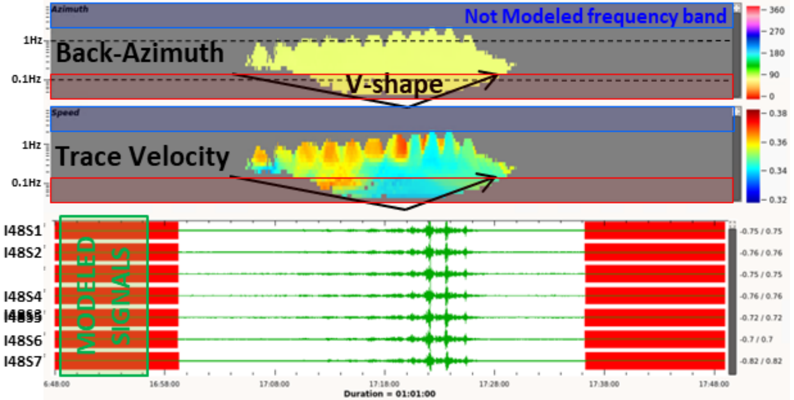
The « V-shape » is well restored by simulation and is also a propagation effect. It is due to the interaction of the incident infrasound wavefield with gravity wave small scale structures in the stratopsphere (partial reflections of the high frequencies which corresponding wavelengths can interact with small scale structure size)

Coherent energy of first modeled arrivals have lower frequencies than observed first arrivals. This suggests that **real small scale structures would have smaller vertical wavelengths than the one used for the modeling** (from Gardner)

OBSERVATIONS



SIMULATIONS



ENERGY ESTIMATION : PREPROCESSING (1/2)

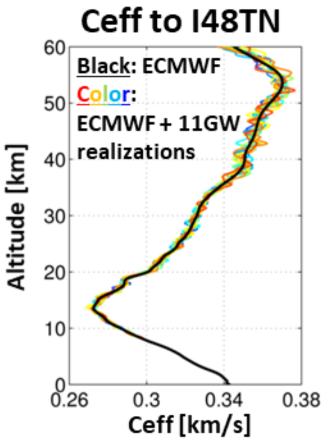
CHOICE OF GRAVITY WAVE REALIZATION

- **Broadband full wave modeling up to 1.2 Hz (W = 500t TNT eq.)**
- **To study the effect of gravity wave realization on arrival times (for localization) and waveform amplitudes (for energy estimation):**
  - **Atmospheric specifications:**
    - → **Mean flow: ECMWF** 137 levels 2020/08/05@00:00 UTC (range-independent)
    - → **Unresolved small scale structures**: **11 gravity wave realizations** from Gardner spectrum (no amplitude correction factor, max amp of perturbation of C_{eff} is **~10 m/s**)

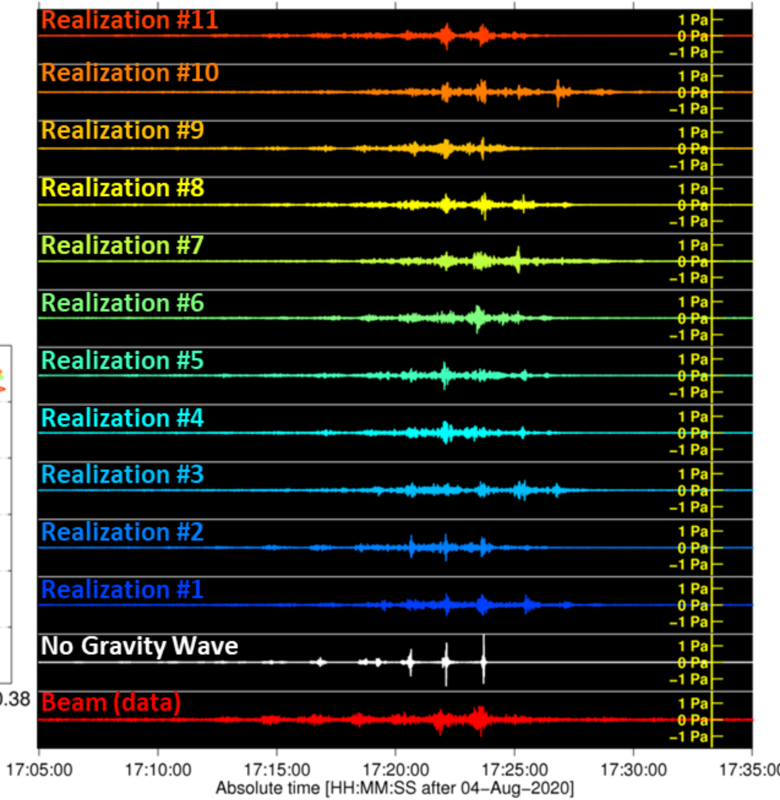
Gravity wave realization controls the number of arrivals and the duration of each arrival

- **Conclusions relative to localization process**
  - **Number of arrivals depends on gravity wave realization**
  - **Each arrival duration depends on gravity wave realization**
  - **Gravity wave realization does not impact significantly arrival time associated to the pick of the maximum amplitude of each phase**
- **Conclusions relative to energy estimation process**
  - **The arrival with maximum amplitude depends on gravity wave realization**
  - **Gravity wave realization does not impact significantly global maximum amplitude (but modeled waveform without gravity wave have much higher amplitude…)**

Realization #11 provides the best fit



Simulations for 11 realizations of gravity waves



ENERGY ESTIMATION : PREPROCESSING (2/2)

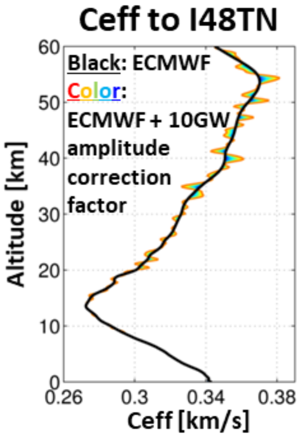
CHOICE OF GRAVITY WAVE AMPLITUDES

- **Broadband full wave modeling up to 1.2 Hz (W = 500t TNT eq)**
- **To study the effect of the amplitude of gravity wave perturbation on arrival times (for localization) and waveform amplitudes (for energy estimation):**
  - **Atmospheric specifications:**
    - → **Mean flow: ECMWF** 137 levels 2020/08/05@00:00 UTC (range-independent)
    - → **Unresolved small scale structures**: **1 gravity wave realization (#11)** and **10 values of Amplitude Correction Factor between 0.2 and 2** (max **amplitude of perturbation between 1 m/s and 20 m/s**)

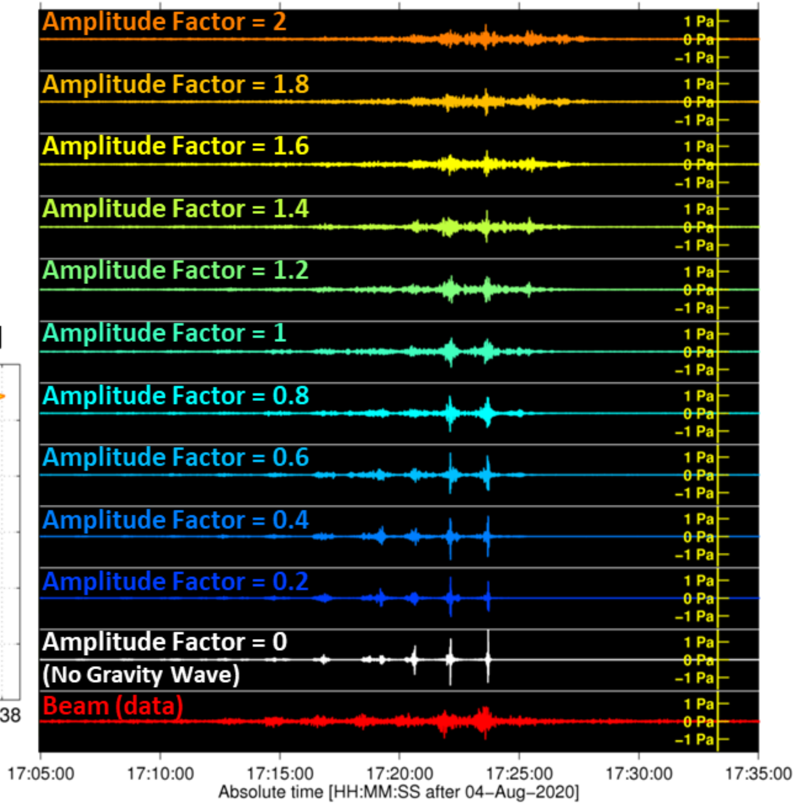
Gravity wave amplitude controls the Amplitude / Duration parameters (by scattering effect)

- **Conclusions relative to localization process**
  - **Number of late arrivals depends on gravity wave amplitude**
  - **Each arrival duration highly depends on gravity wave amplitude**
  - **Gravity wave amplitude does not impact arrival time associated to the pick of the maximum amplitude of each phase**
- **Conclusions relative to energy estimation process**
  - **The arrival with maximum amplitude does not depend on gravity wave Amplitude Correction Factor**
  - **Gravity wave amplitude impacts significantly global maximum amplitude (by a factor of 2)**

Amplitude Correction Factor between 1 and 1.2 provides the best fit (max amplitude of perturbation ~10m/s)



Simulations for 10 values of GW Amplitude Correction Factor



SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Poster No.: P1.1-401

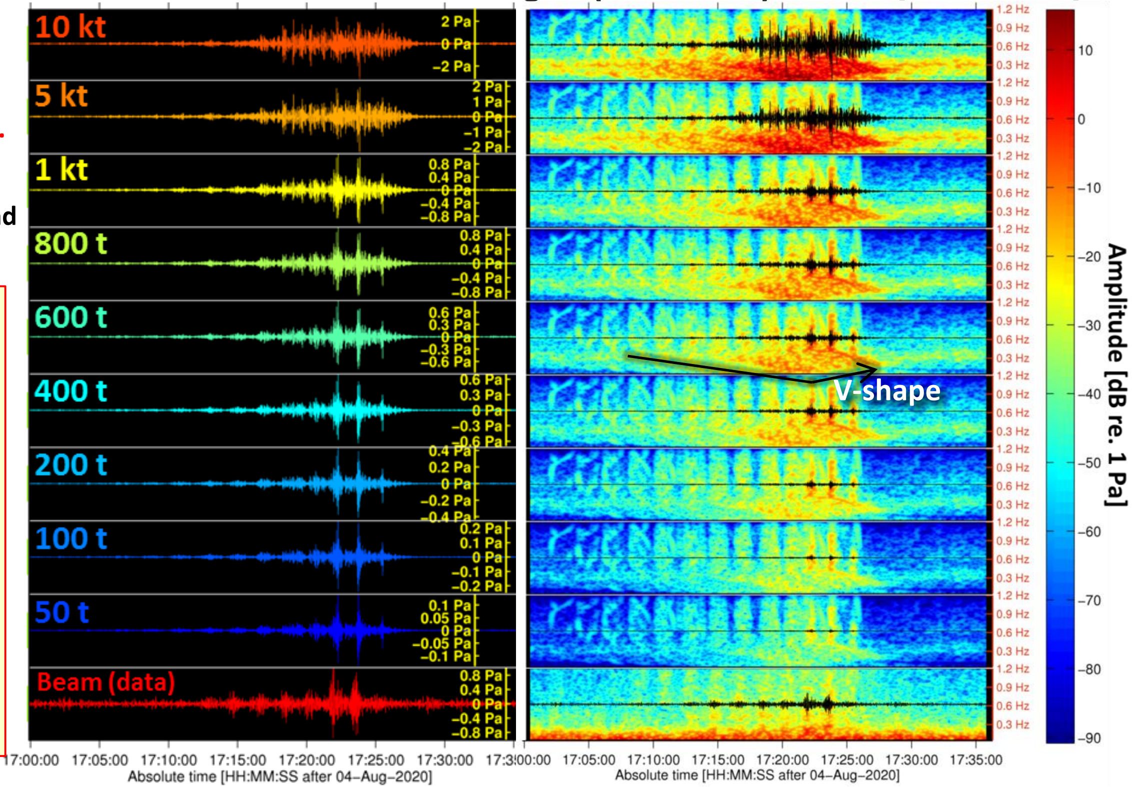
ENERGY ESTIMATION FROM IMS INFRASOUND-ONLY DATA

cea

- To estimate the acoustic energy of the event, gravity wave realization and Amplitude Correction Factor are chosen from previous sensibility study
  - Realization #11 and Amplitude Correction Factor = 1.2
- 9 values of energies are tested, between 50t and 10kt TNT eq.
- Broadband full wave modeling up to 1.2 Hz
- Fit is performed from comparison of time series envelopes and spectral levels in [0.2 Hz – 1.2 Hz] frequency band

- Best fit is obtained for yield within 400t – 600t TNT eq. range from I48TN, I17CI and I11CV (only I48TN shown here)
- I42PT was not used (too noisy)
- Modeled I26DE amplitudes are 2 to 3 times too high
  - Probable explanation : bounces occur over topographic areas (not modeled), unlike paths to other stations (over sea/desert)
- 1 kt is excluded, 800 t is very unlikely (estimated from low frequency levels, below 0.2 Hz)
- Validation: the same methodology was applied for the 26 August 2009 Sayarim 1 infrasound event (W = 96 t, [Fee et al., 2013]).
  - The two events are comparable in termps of source location, propagation conditions and remote detecting stations

Simulations for 9 values of energies (50t->10 kt) -- Filter : [0.2Hz - 1.2 Hz]



SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

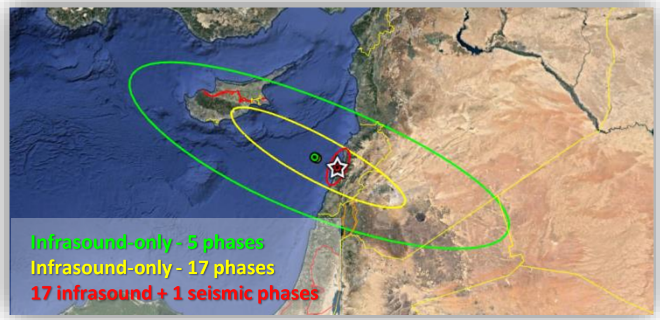
Poster No.: P1.1-401

LOCALIZATION

INFRASOUND-ONLY LOCALIZATION VS INFRASOUND + 1 SEISMIC ARRIVAL

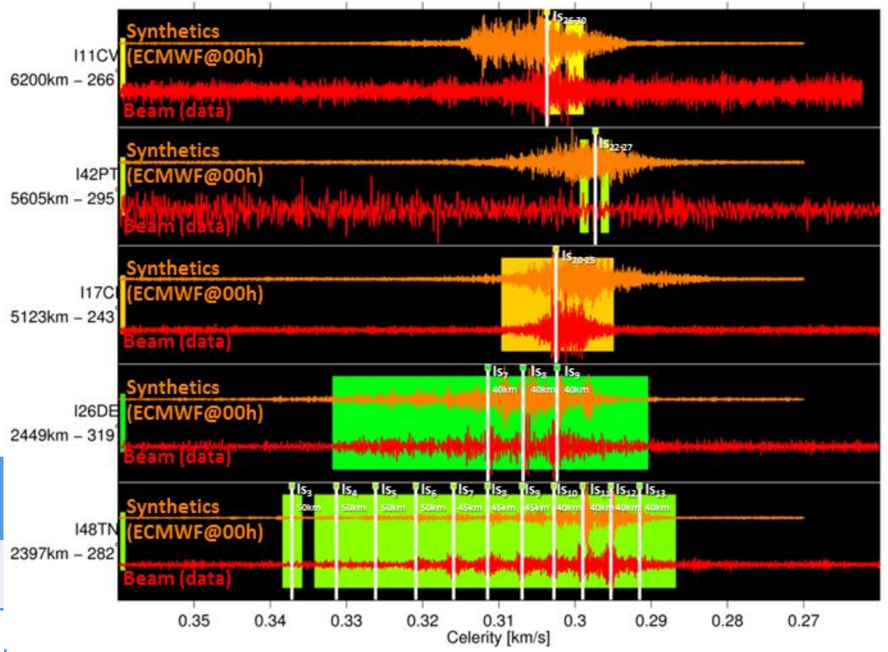
- **Construction of propagation tables (phase-dependent velocity models and azimuth deviations) from ECMWF analysis model (2020/08/05@00:00 UTC)**
  - **Velocity models are extracted from max amplitudes of modeled waveforms (range-independent)**
  - **Azimuth deviations are calculated from 3D ray tracing modeling (phase identification on figure)**
- **Model uncertainties: σ_{vel} = 5 m/s, σ_θ = 2°**
- **Measure uncertaintes associated to extraction features are neglected (max amp are picked)**
- **3 localizations are calculated:**
  - **Yellow: with 17 infrasound arrivals from 5 stations**
  - **Green: with 5 infrasound arrivals (one per station, arrival with the highest amplitude) from 5 stations**
  - **Red: with 17 infrasound arrivals and 1 seismic arrival (GEM, 77km) from 6 stations**

Localization uncertainties remain quite high using infrasound-only data, despite the used *in depth* methodology (limiting factors: spatial distribution of remote detecting stations, propagation directivity, slow propagation medium)



Δloc km	Δt_0 MM:SS	95% Ellipse surface km²
44 km	+02:07	17 900 km² (190x300)
48 km	+01:56	128 650 km² (390x105)
2 km	-00:03	1 760 km² (35x16)

Data, synthetics and phase identification



The size of the infrasound-only confidence ellipses (green and yellow) remain large because of the ambiguity between origin time and spatial location

With one single sesimic arrival (red), the ambiguity disapears (t0 is known)

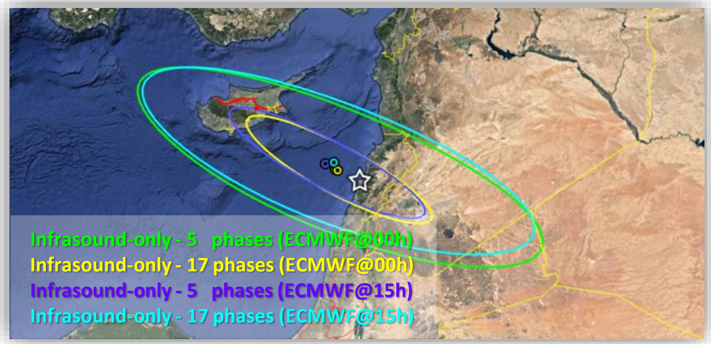
LOCALIZATION

INFRASOUND-ONLY LOCALIZATION: ECMWF ANALYSIS VS ECMWF FORECAST

- Same localization methodoly is applied from ECMWF 2020/08/04@15:00 UTC model
  - New netcdf products distributed by the IDC (time resolution: 1 hour, spatial resolution: 0.25° x 0.25°)
  - ECMWF 2020/08/05@00:00 : ECMWF <u>analysis</u> (most recent data are assimilated)
  - ECMWF 2020/08/04@15:00 : ECMWF <u>forecast</u> (provided by run at 00:00)
- Surprisingly, synthetics calculated from ECMWF 2020/08/04@15:00 generally fit worse the data than synthetics calculated from ECMWF 2020/08/05@00:00 (especially at I48TN and I26DE)
  - This suggests that forecast models in the stratosphere would be less performant than in the troposhere?
  - Arrival celerities shift within 3-5m/s at I48TN and I26DE, depending on phase
  - But predicted amplitudes are not impacted (ducts remain the same)

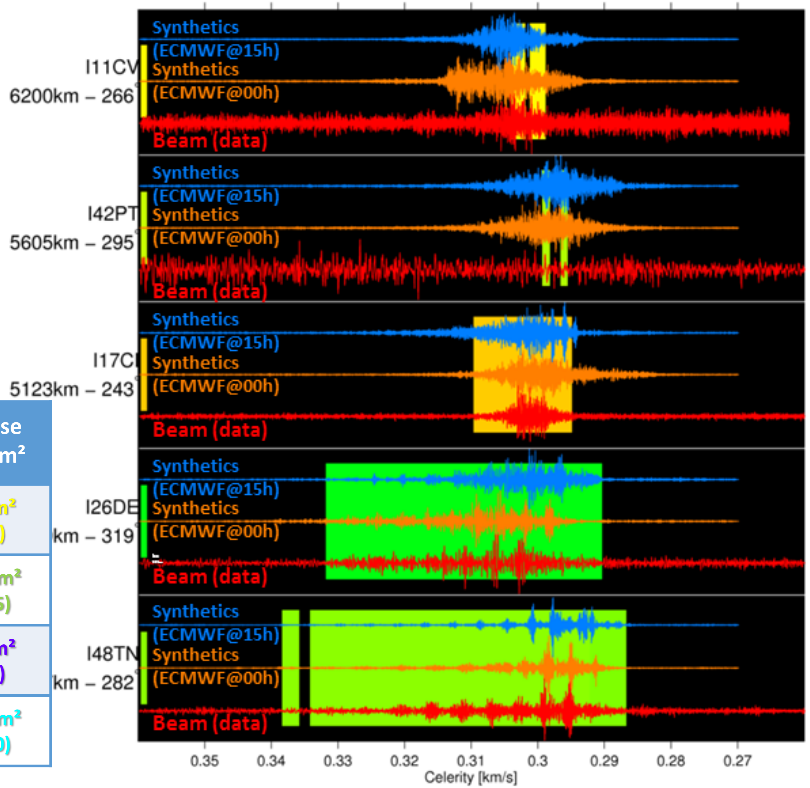
Despite worse fits using ECMWF 2020/08/04@15:00 UTC model (forecast), <u>estimated localizations remain close</u> (considering infrasound uncertainties) to the ones obtained from ECMWF 2020/08/05@00:00 model (analysis)

<u>Energy estimation is not impacted</u>



Δloc km	Δt_0 MM:SS	95% Ellipse surface km²
44 km	+02:07	17 900 km² (190x30)
48 km	+01:56	128 650 km² (390x105)
70 km	+02:29	27 000 km² (200x43)
60 km	+02:26	135 800 km² (390x110)

Data and synthetics (ECMWF at 00h and 15h)



Disclaimer: The views expressed on this poster are those of the author and do not necessarily reflect the view of the CTBTO

CONCLUSION

- In this presentation, **special focus is given to the in depth interpretation of I48TN data** (closest IMS infrasound station at 2400 km)
- **Frequency-dependent detection patterns are well explained** and are a combinaison of local uncoherent background noise and long range propagation effects (eg: decrease of trace velocities over time)
  - We quantify here the **benefit to finely characterize the infrasound wavefield in the time-frequency space** (DTK-GPMCC is used)
  - Ongoing: vertical wavelengths of gravity waves could be inferred from arrival-dependent coherent frequency bands
- Full-wave modeling technics was massively used. It allows to understand the **effect of gravity waves on modeled waveforms** and to **quantify its impact on event characterization and event localization**
- Energy estimation from IMS infrasound-only data provides the **most likely yields within 400 t – 600 t TNT eq. range**
- **Energies over 1 kt TNT eq. are excluded (from spectral levels under 0.2 Hz)**
- Despite a **complex but precise phase identification**, **localization uncertainties using infrasound-only IMS data remain large**. **These uncertainties are reduced by a factor of 10 to 50 if only one seismic arrival time is used**
- The use of **ECMWF forecasts** at event origin time (2020/08/04 15:00) provides slightly worse localization results than **ECMWF analysis** at 2020/08/05-00:00
  - This result suggests that forecasts in the stratosphere would be less performant than at tropospheric altitudes → *Ongoing study…*