DE LA RECHERCHE À L'INDUSTRIE

Bayesian calibration of GT events from stochastic models

C. Millet[1,2], M. Bertin[2], J. Vergoz[1], P. Mialle[3]

[1] CEA, DAM, DIF, F-91297 Arpajon
[2] CMLA, ENS Paris-Saclay, F-94235 Cachan
[3] CTBTO, Vienna, Austria

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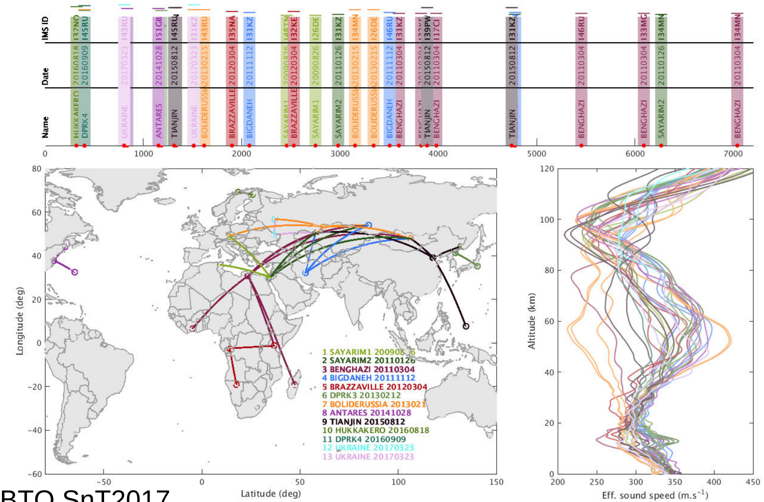
Context
Selected GT events

Ground-Truth events as a function of distance (km)



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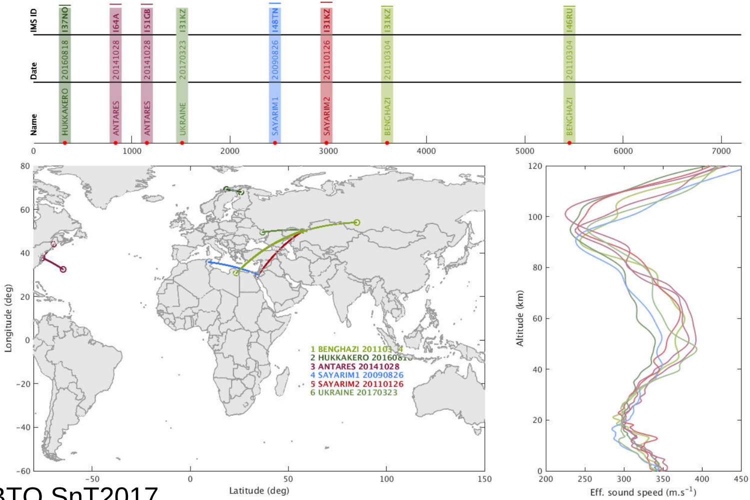

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- 1. Stochastic simulation with reduced models
- 2. Bayesian calibration of selected GT events
- 3. The ‘weight’ of gravity waves in simulations

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Infrasound propagation modeling

- In most modeling works, acoustic component is superimposed on a given atmospheric state (provided by NOAA, ECMWF, ...).
- Classical "full-wave" linear techniques are known from the 80's: PE method, normal modes, finite element method (FEM), ... All these methods involve basically computing

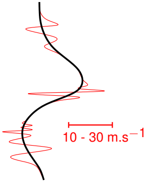
$$AX = Y, \quad (1)$$

with $A \in M_N(\mathbb{C})$; X: acoustic perturbation; Y: source.
- Solution: $X = A^{-1}Y$ or through the eigenproblem

$$P^{-1}X = D^{-1}(P^{-1}Y) \text{ with } D = \text{diag}(\lambda_1, \ldots, \lambda_N).$$

Impact of small scales on infrasound signals

- Matching processes of atmospheric data and unresolved variability in GCMs introduce large deviations and subgrid-scale structures in the sound speed profile.
- FEM is suited to capture the effect of these structures, but it requires a large amount of computer time (10^8 elements at 1 Hz for domains 1000 km x 180 km).



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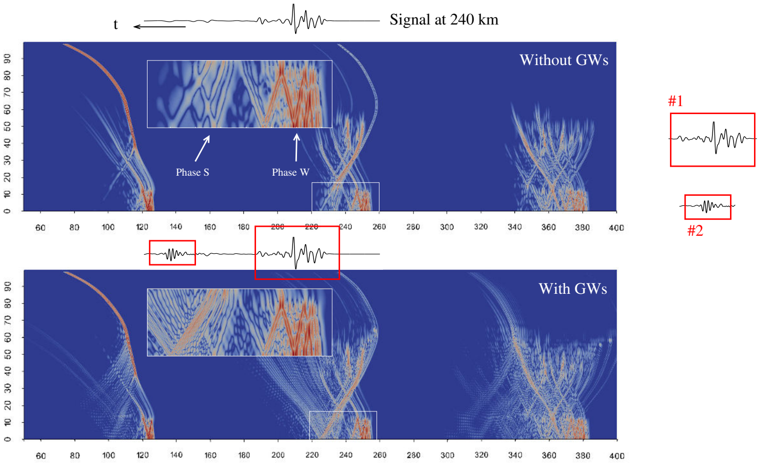
Finite Element Method for Sayarim II (20110126)

- FEM useful as a tool for benchmarks (North-East direction)



Lagrange P2-Bubble finite elements, mass lumping procedure, use of MPI library.
FreeFem++: FEM in cylindrical coordinates with absorbing boundary conditions (PML).

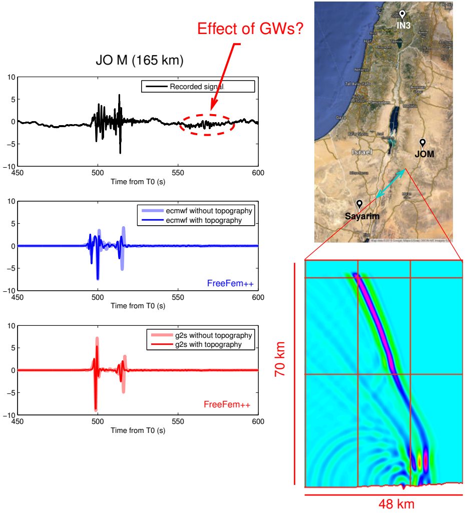
Finite Element method vs observations at JOM (Sayarim II)

- A **single** run is enough...

  For computing short-range acoustic fields (up to 200 km);

  For predicting waveforms (and by-products) of W phases.

  For estimating role of topography.



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○○●○○ Stochastic simulation with RM
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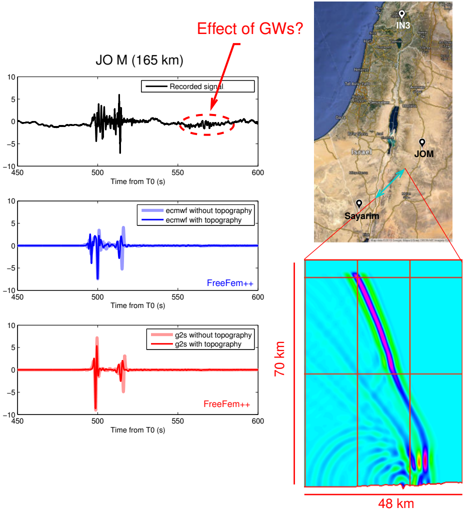
- Need several runs in other cases.

  The larger the sample size, the smaller the confidence interval.



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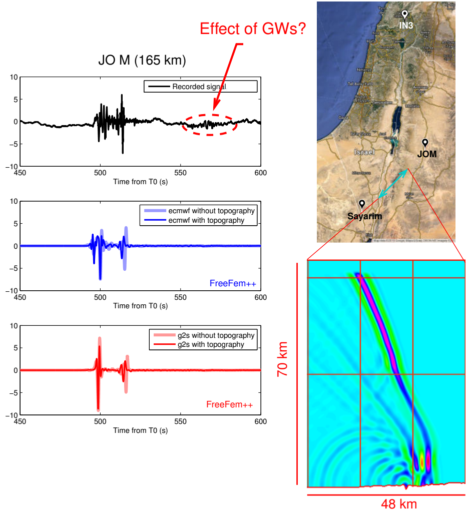
- What can we do in a finite world?

  Useless to compute highly unlikely or vanishingly small wavepackets.

  Better to consider more plausible cases instead of computing 0.0's.



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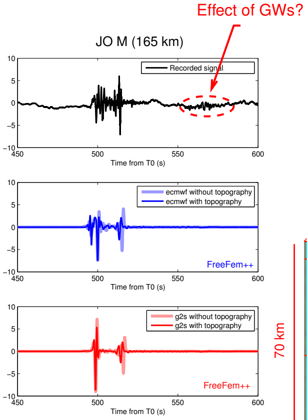

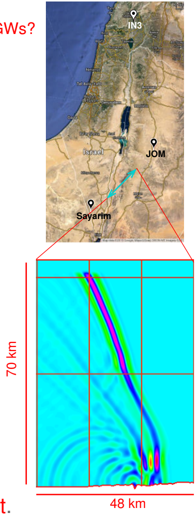

Given (numerical/physical) complexity, our goal is to extract most relevant statistics from large dimensional problems at fixed CPU budget.

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The reduced basis approach

- Analogy: atmosphere = wind instrument.
  - The atmosphere is a vibrating medium.
  - Atmospheric states are "fingerings" which are the result of complex motions within the instrument.
  - Sheet music is provided by ECMWF.

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These modes = reduced model of the instrument. The reduced model can be used to identify the player (or how the player's lips vibrate), for given sheet musics.

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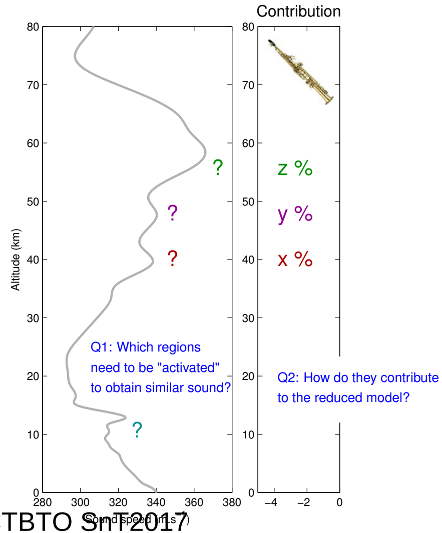
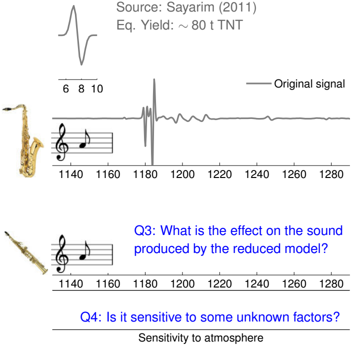
Illustration: Sayarim II event (20110126), IN1



- Sounds with reduced models.
  - # Modes 00.0%
- Computed signals.
  - IN1 station (322 km).



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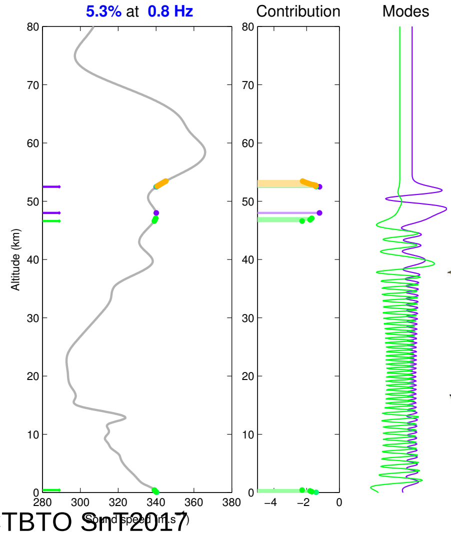
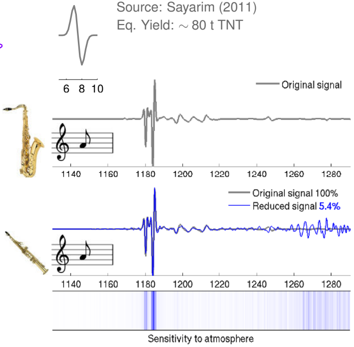


- Sounds with reduced models.
  - # Modes **05.4%**
- Computed signals.
  - IN1 station (322 km).

Source: Sayarim (2011)
Eq. Yield: ∼ 80 t TNT



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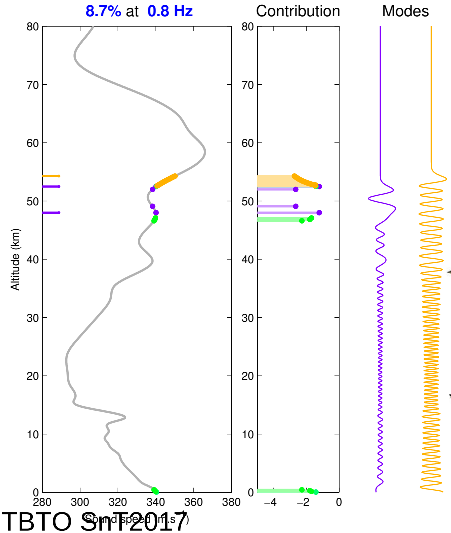
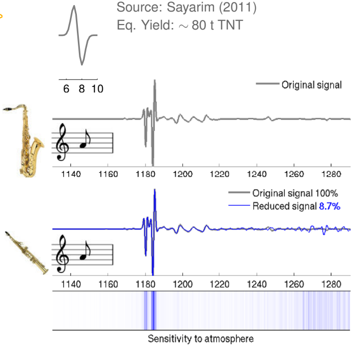
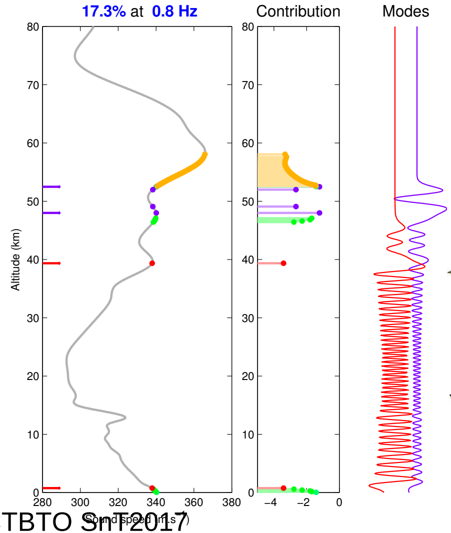


- Sounds with reduced models.
  - # Modes 08.7%
- Computed signals.
  - IN1 station (322 km).

Source: Sayarim (2011)
Eq. Yield: ∼ 80 t TNT

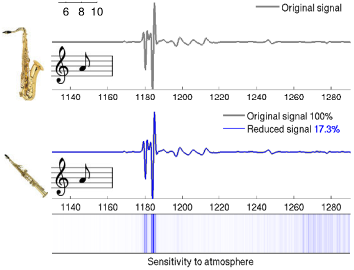


○○○○● Stochastic simulation with RM
Illustration: Sayarim II event (20110126), IN1



- Sounds with reduced models.
  - # Modes 17.3%
- Computed signals.
  - IN1 station (322 km).

Source: Sayarim (2011)
Eq. Yield: ∼ 80 t TNT



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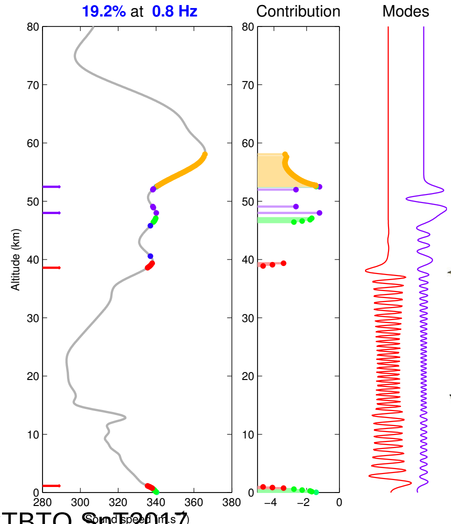
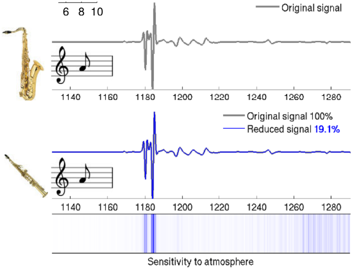


- Sounds with reduced models.
  - # Modes 19.1%
- Computed signals.
  - IN1 station (322 km).

Source: Sayarim (2011)
Eq. Yield: ∼ 80 t TNT



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- 1. Stochastic simulation with reduced models
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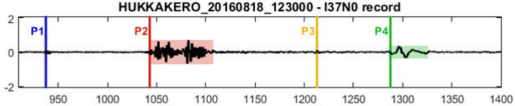
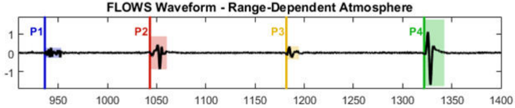
Quantities of interest for a signal at I37NO (Hukkakero, 20160818)

- Quantity of interest $\Delta = \{t_n, A_n, \tau_n\}_{n=1,\ldots,4}$.
  - t_n: arrival time of wavetrain n;
  - A_n: maximum amplitude of wavetrain n;
  - τ_n: duration of wavetrain n.



D: recorded t, A, τ



Δ_j: simulated t_j, A_j, τ_j
Source specifications?

- Uncertainties are described by pdfs that depend on hyperparameters θ_j
  1. For fixed plausible θ_j the reduced model M can be used to provide signals from which the pdfs of Δ are extracted.
  2. Estimate the posterior pdf of θ_j, given an observation D, through bayesian inference.

$$p(\theta_j|D) = \frac{p(D|M,\theta_j)p(\theta_j)}{p(D|M)}.$$

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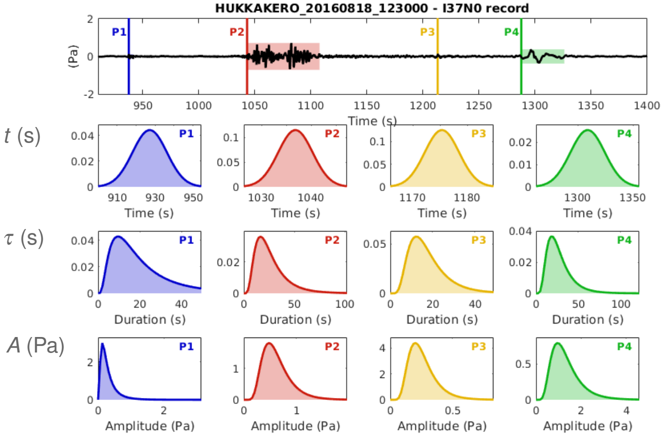
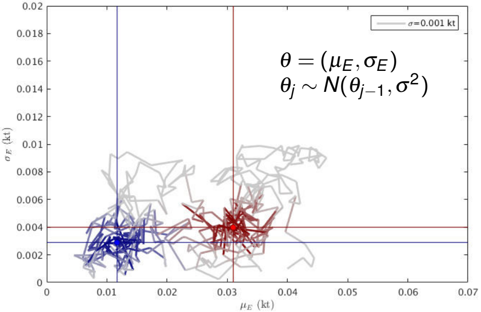
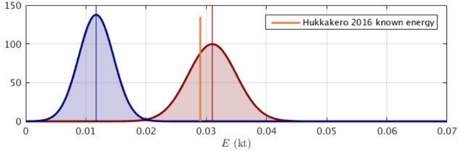
- For 10^3 realizations (range-dependent reduced model M) for fixed θ_i's.

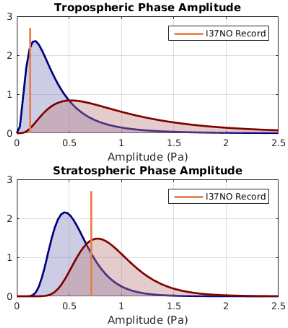


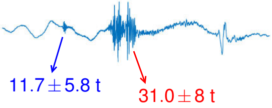
Atmospheric uncertainty is given by a gaussian stationary process.

2. A Markov Chain Monte Carlo approach to estimate energy









$P(|E - \mu_E| < 2\sigma_E) = 0.9545$

Energy estimate: gaussian distribution of mean μ_E and std σ_E.

10^6 simulations (10^3 iterations x 10^3 signals per iteration).

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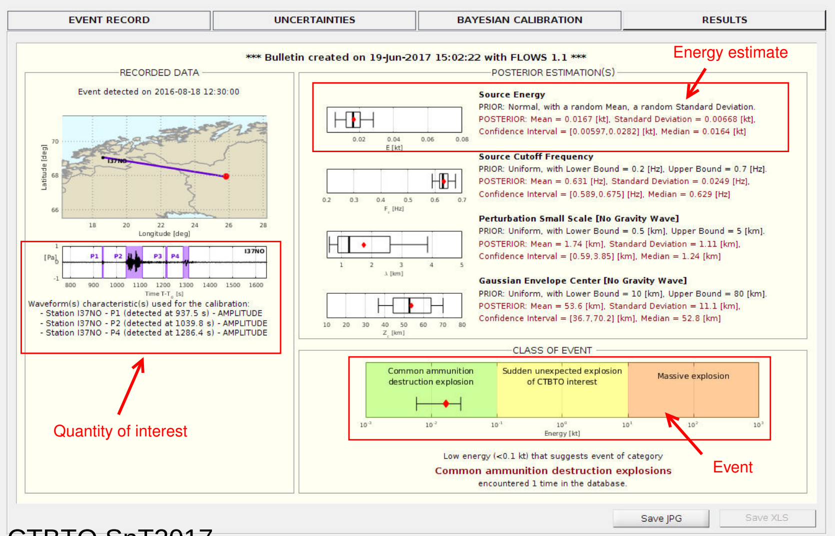
○○○●○ Bayesian calibration of GT events
A FLOWS 'bulletin' obtained from 10^6 signals (Hukkakero, 20160818)



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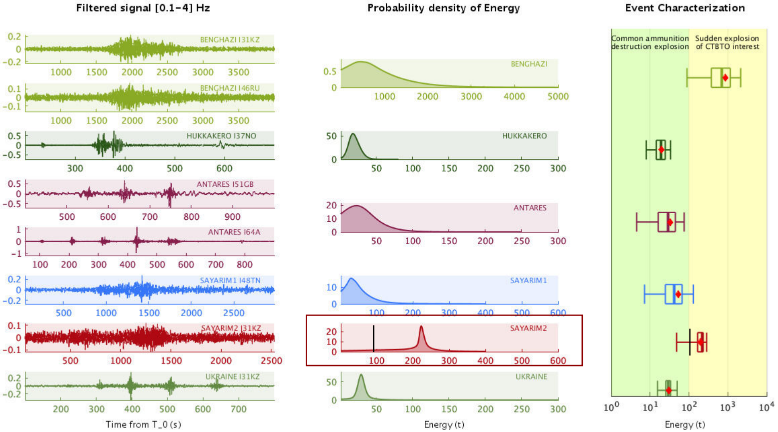
Other selected events: Benghazi, Antares, Sayarim I & II, ...

- Other energy estimates and class of events.



Bayesian inference overestimates the energy for Sayarim II event.

What is the impact of GWs on the energy estimate?

- 1. Simulation with reduced models
- 2. Bayesian calibration of selected GT events
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The relativity of small scales

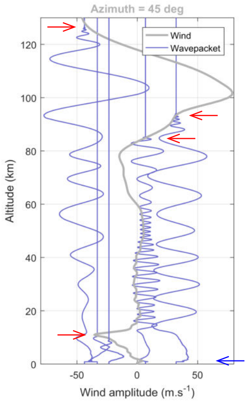
- Stochastic GWs.
  - GWs are an important driver of the circulation of the middle atmosphere. Their spatial scales are *too small* to be represented in GCMs and thus, their effects on resolved scales is parameterized.
  - As the mechanisms of GW emissions are unclear, sources can be seen as stochastic processes.
- Stochastic GW parameterizations.
  - Recent observations (Wright *et al.*, 2013) show that GWs often travel as wave packets $w'_n(\mathbf{x}, z, t)$.
  - Multiwave schemes are linked to GW sources.

$$w' = \sum_n C_n w'_n \text{ with } \sum_n C_n^2 = 1$$

$$w'_n = \mathrm{Re}(\hat{w}_n(z) e^{z/(2H)} e^{i(\mathbf{k}_n.\mathbf{x} - \omega_n t)})$$

C_n^2: probability that the field is realized entirely by the nth wave. Launched EP flux F^z, k_n and phase velocity are randomly chosen.

  - The typical vertical scale can be locally larger or smaller than the acoustic wavelength.



GWs propagate upward from z_0.
GWs break when $\omega - \mathbf{k}.\mathbf{U} = 0$

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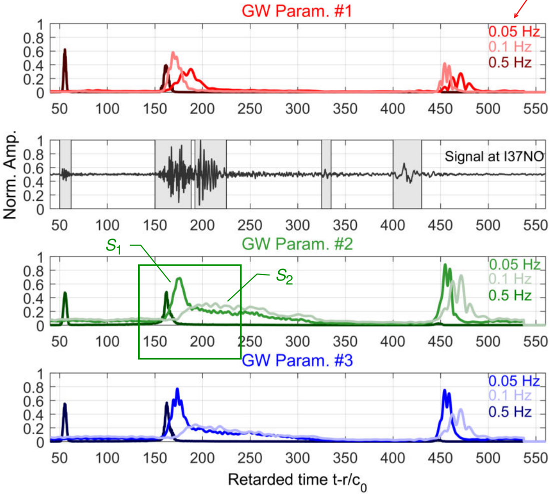
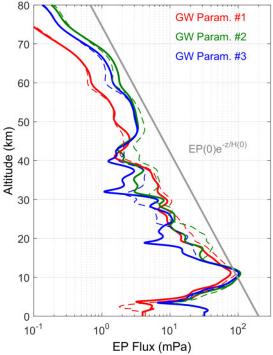
The ‘weight’ of GWs
A new GW model and its impact on simulated signals (Hukkakero, 20160818)

Normalized Standard deviation $\sigma(t)$ (Hukkakero, 20160818)

Source central freq. f_c



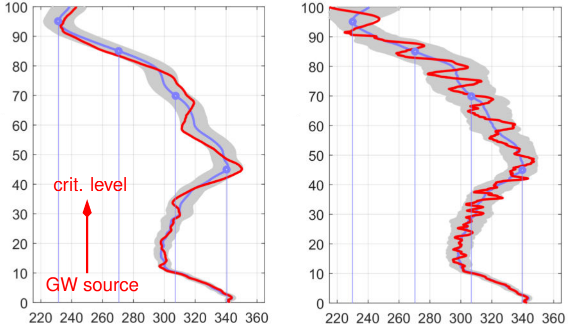


Observations* ~ 20 mPa at 20 km
Orography ~ 100 mPa

In the new model, the GW sources are distributed over the troposphere

The sensitivity of second arrival (phase S) depends on f_c and on the GW sources.

- Uncertainties in the atmosphere.
  - Stoch. processes are not stationary (two given altitudes are correlated).
  - The "amount" of small-scales is essentially related to GW sources.
  - In Numerical Weather Prediction models, only the orography is considered.



Classical GW Param. in use in GCMs

GW Param. adapted to the "Hukkakero" region.

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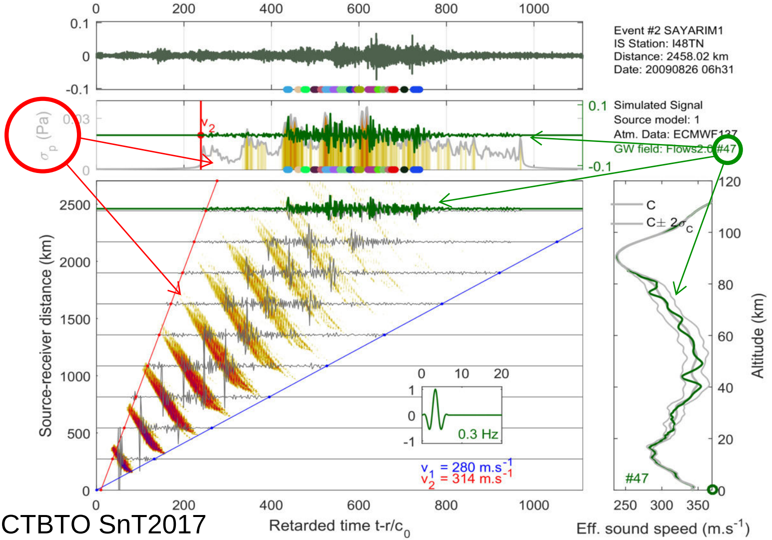
A large-scale event: Sayarim 1, I31KZ (20090826)



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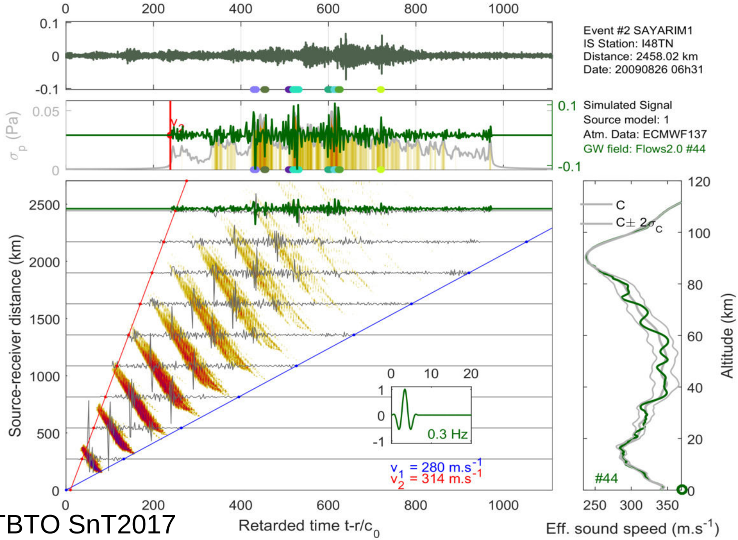

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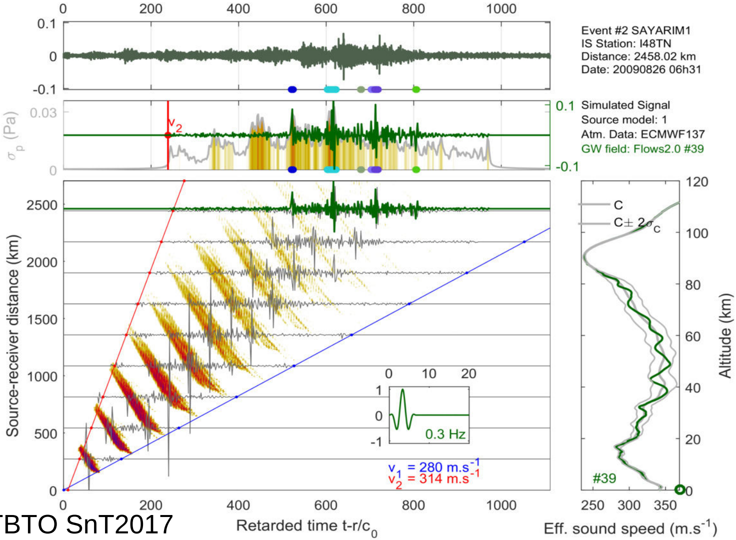

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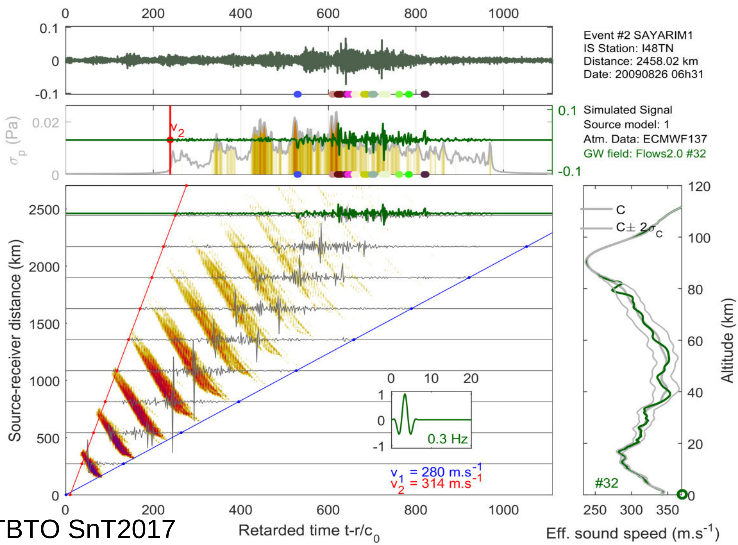

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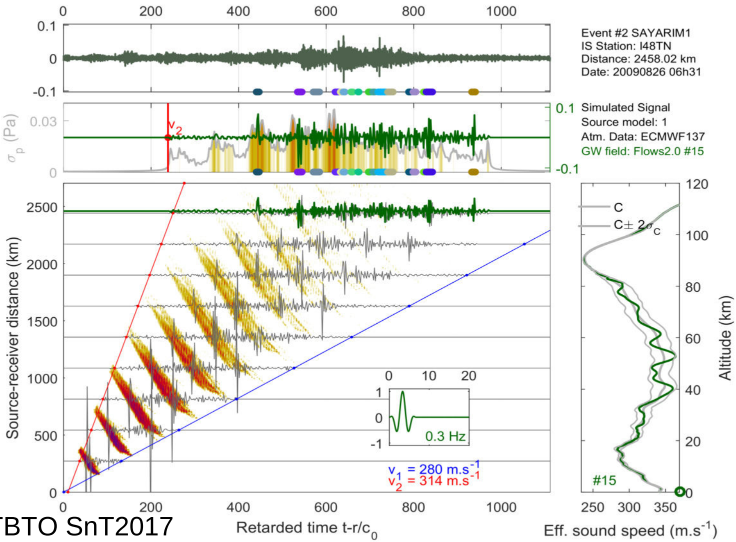

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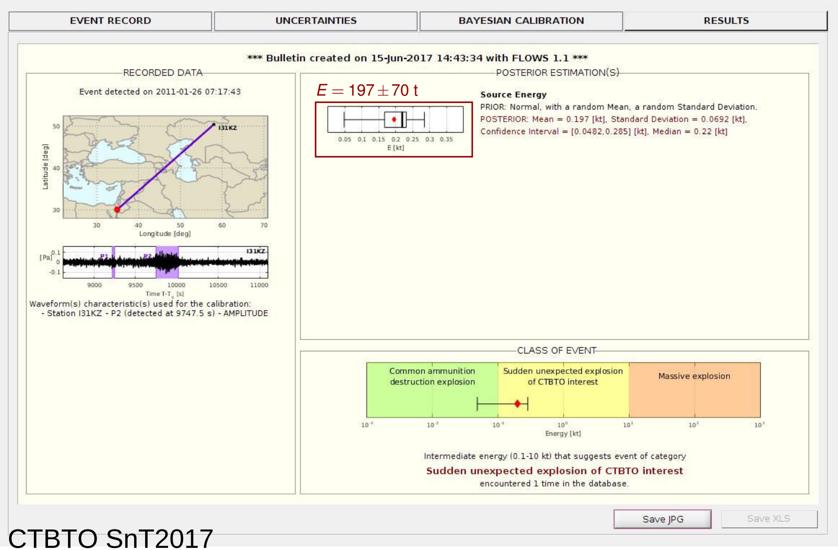
○○○○● The ‘weight’ of GWs
FLOWS ‘bulletin’ for Sayarim 1 from I31KZ



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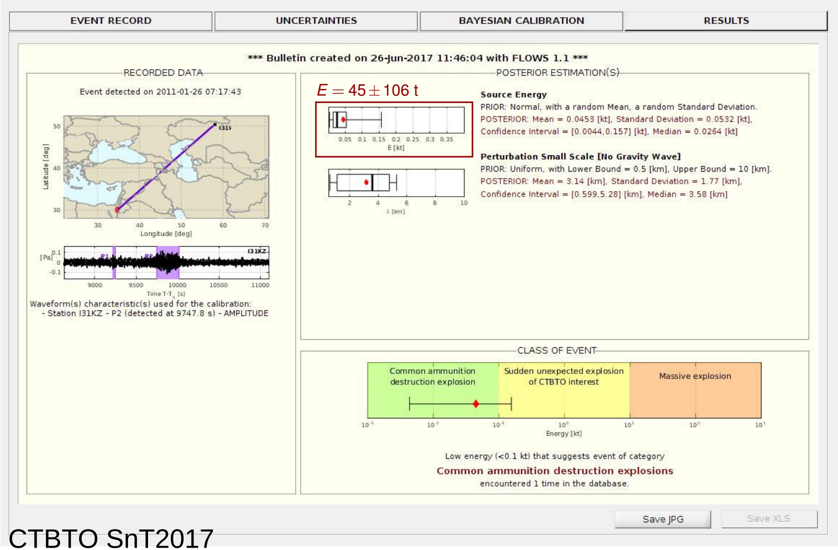

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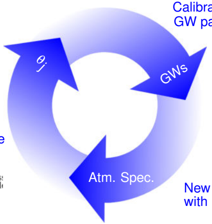
Conclusion and perspectives

- Stochastic simulation with reduced models.
  - Compute modes that most contribute to statistics with high resolution methods (spectral method) and disgard unlikely/vanishingly small part.
- What have we learnt from the bayesian modulus FLOWS 1.1?
  - The energy estimate depends on the quantities extracted from records, the atmospheric perturbation model and the source model.
  - Ignoring the effect of atmos. unknowns introduces a bias in the estimate.
- Next? Towards a new generation of climate models.
  - Use the "background acoustic noise" recorded at the IMS stations and machine learning techniques to calibrate the GW parameterization in FLOWS 2.0 for each region covered by GT events.

Calibration of
GW parameterizations



Bayesian inference
of known events

New atmos. specification
with NWP models

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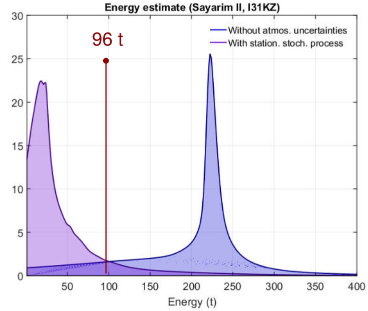
A summary of the impact of atmospheric uncertainties.

- Using atmospheric specifications provided by ECMWF overestimates the energy.
- Adding a stochastic stationary process underestimates the energy.



What is the impact of the new GW parameterization? The answer will be given at the *Infrasound Technology Workshop*.

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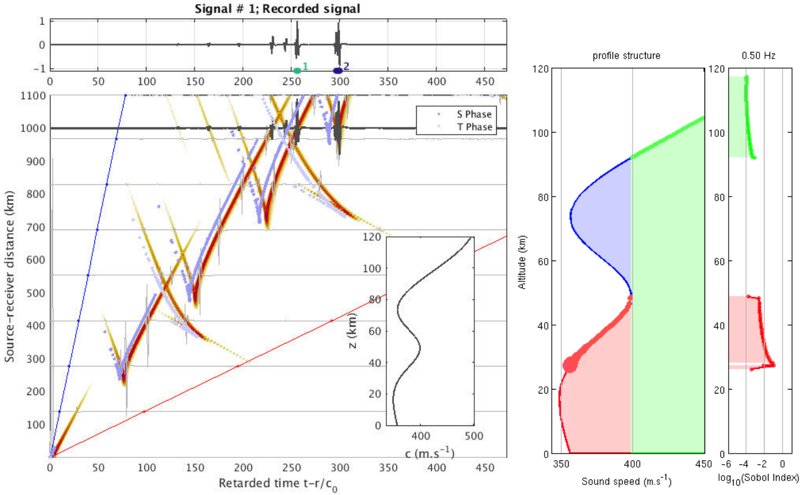
Reduced basis approach (extra material)



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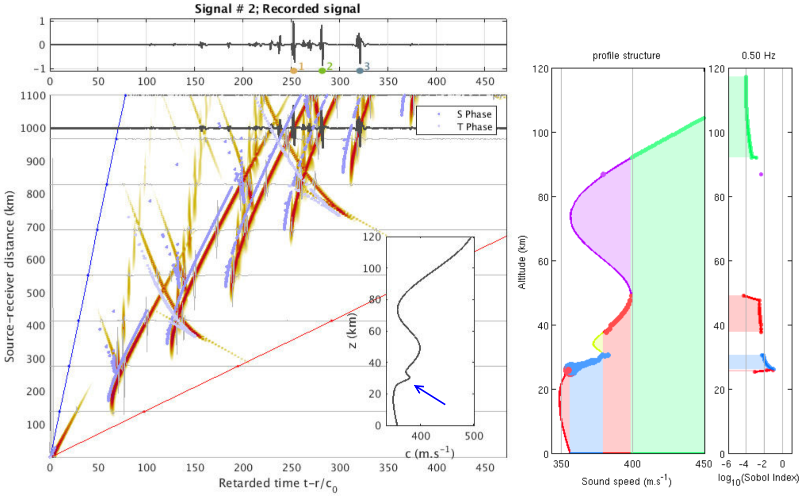
Reduced basis approach (extra material)



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