Prompt earthquake detection based on transient gravity signals

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Context

The deformation caused by an earthquake induces changes in the Earth's gravitational field known as coseismic gravity changes, immediately and remotely. Superconducting gravimeters and satellite missions have observed *static* gravity changes from before to after several large earthquakes [1]. The aim of our study is to search for and detect gravity signals from earthquakes *during* the rupture. A first tentative of detecting the fault rupture during the Tohoku Mw = 9.0 earthquake is made with the analysis of data recorded by the superconducting gravimeter in Kamioka (Japan). We also used analytical expressions and numerical simulations using normal mode theory [2] to estimate the gravity time series.

Detection of a prompt gravity signal from the 2011 Tohoku-oki earthquake

We analyze the data of the super event of Mw = 9.0 Tohoku earthquake, recorded by state-of-the-art superconducting gravimeter :

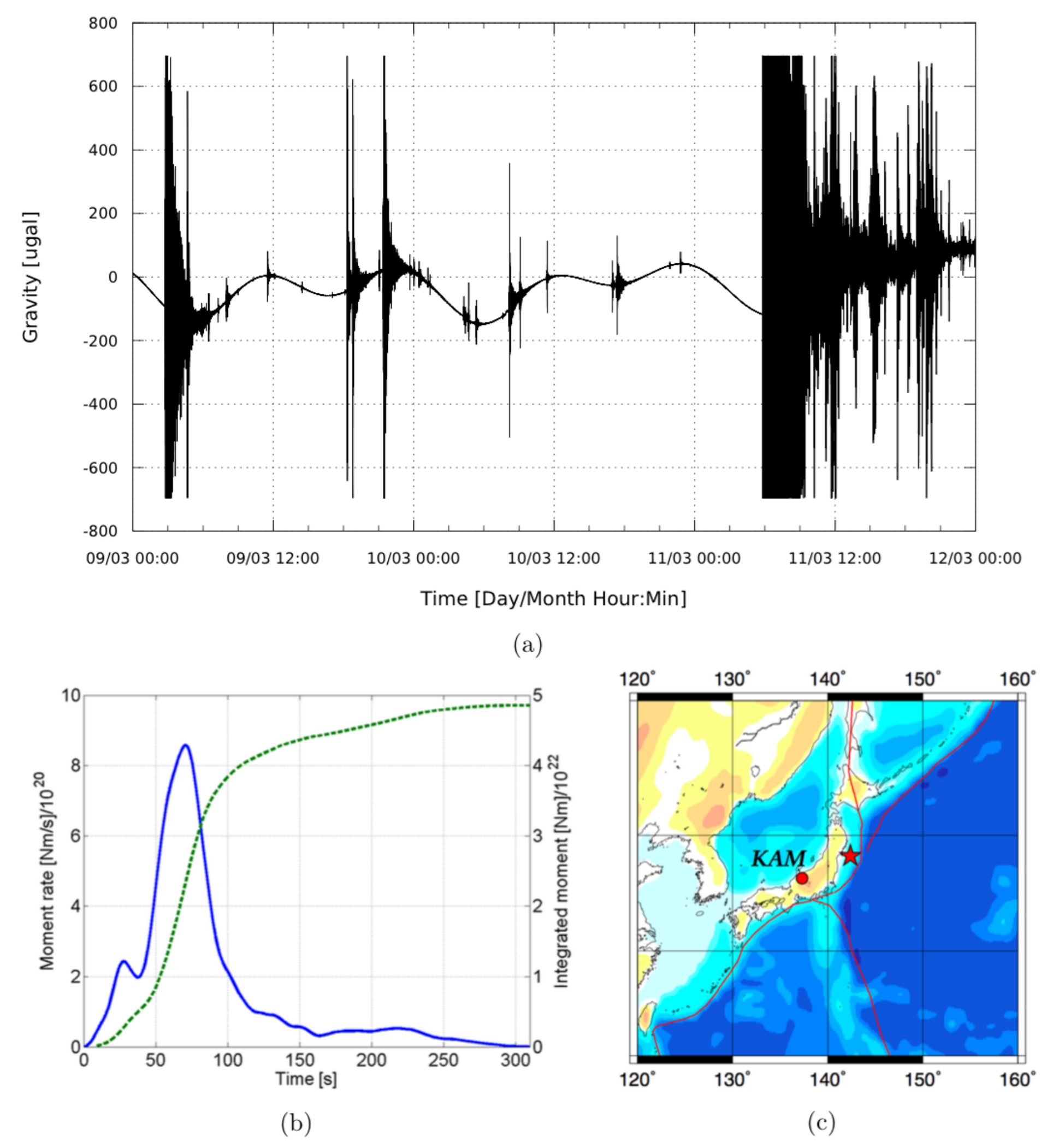

Figure 1 : (a) : Recording of the gravity field by a superconducting gravimeter at the Kamioka station. (b) : Source-time function for the 2011 Tohoku-oki earthquake. (c) : Respective locations of the event (red star) and the Kamioka observatory.

The transient gravity signal associated to the event is expected to be small. In the raw data, this signal, if present, does not clearly stand out above the ambient seismic noise : we need a blind detection procedure.

We apply a polynomial curve fitting algorithm on background data, as described in figure 2. We search objectively for the optimal set of fitting parameters (degree of the polynomial fit, length of the time window). Once the parameters chosen, we apply the algorithm on the Tohoku event window.

We find a signal with a statistical significance of more than 99% (see figure 3).

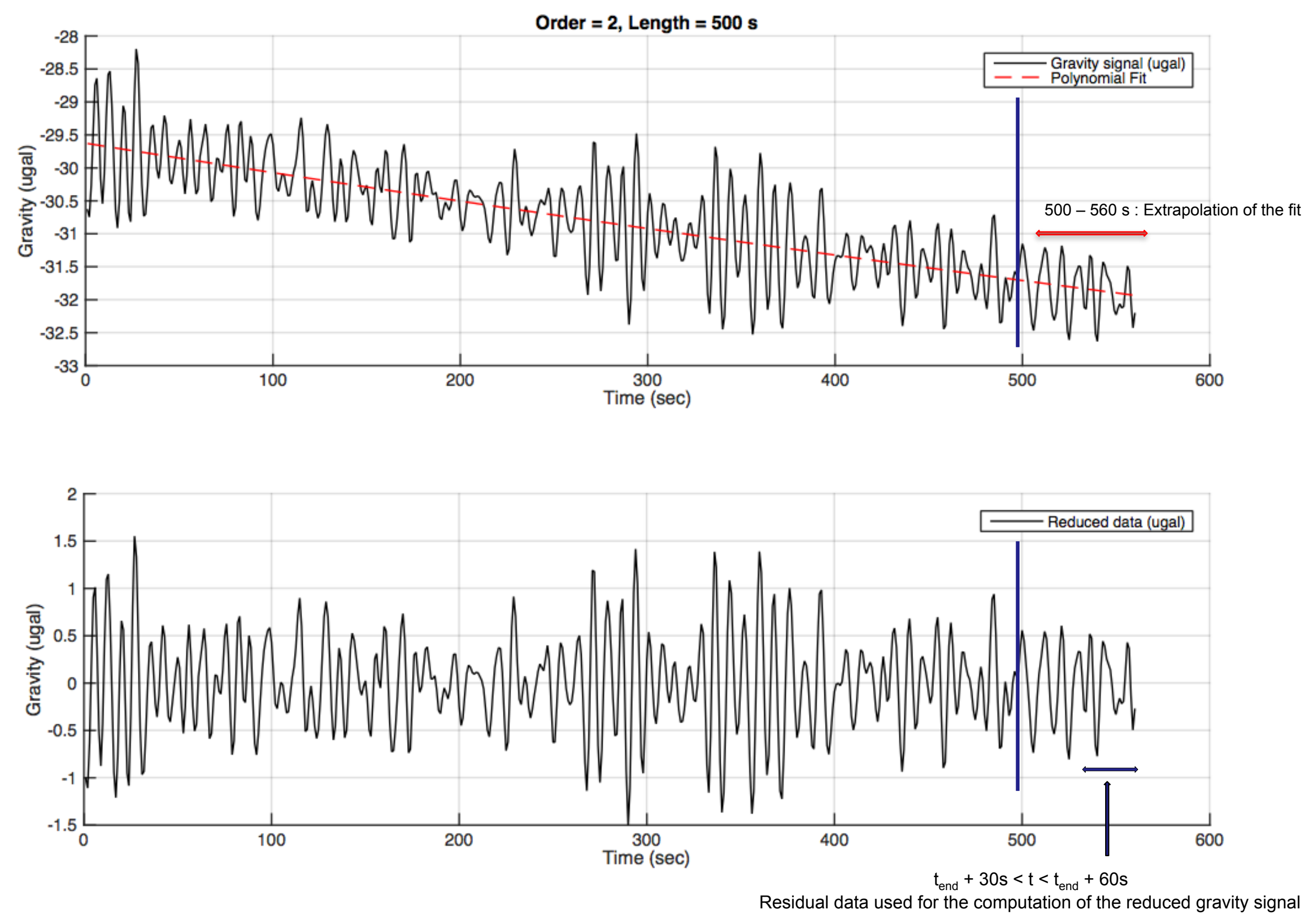

Figure 2 : Signal detection method. Here, the data has been fitted with a polynomial function of degree d = 2 on a window of length T = 500s, which is extrapolated for 60s. We define the reduced gravity signal as the mean of the last 30s of the extrapolation.

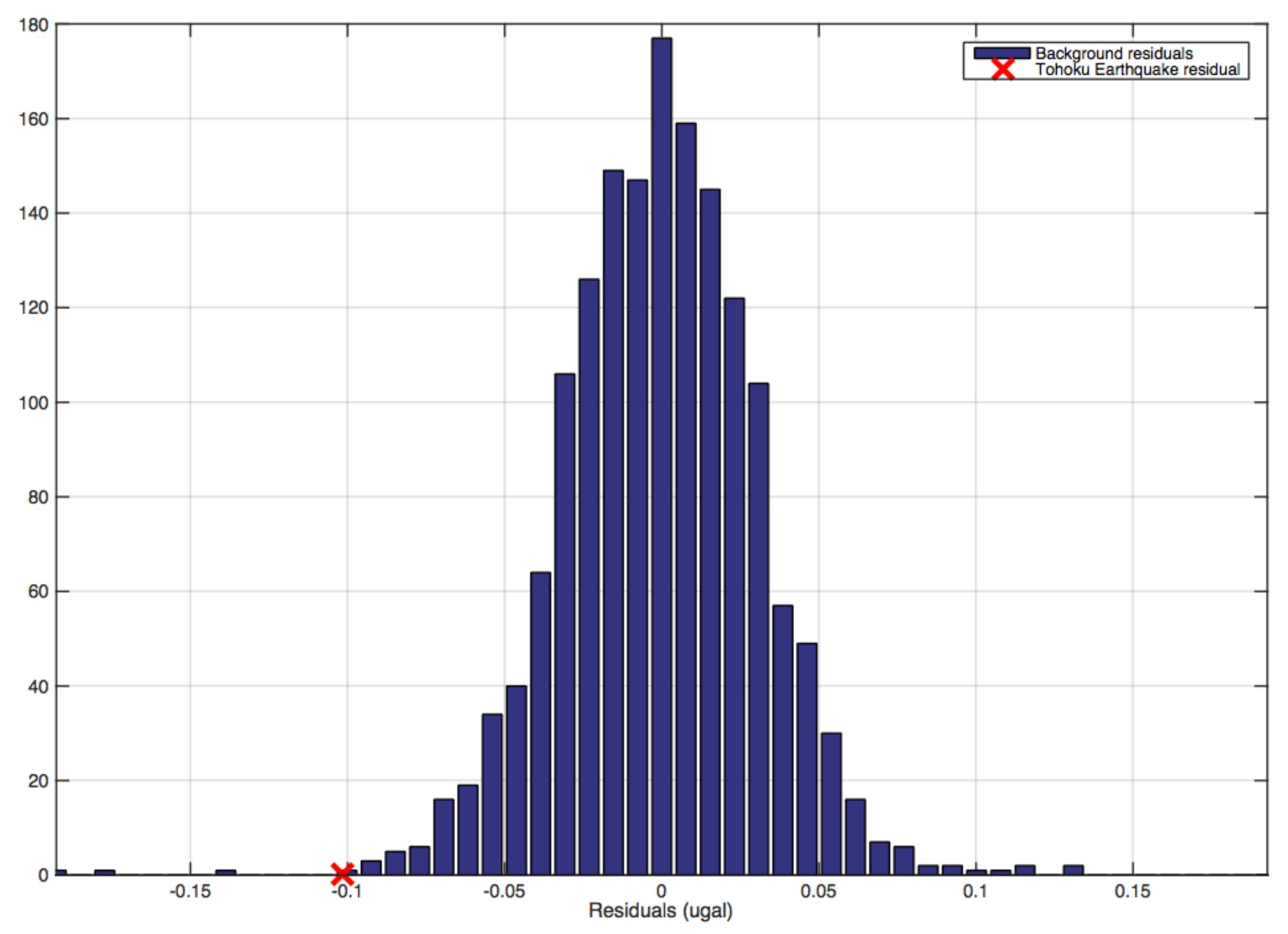

Figure 3 : Result of the blind analysis. Distribution of the reduced gravity signals for the optimal parameters d = 2 and T = 652s. The background reduced gravity signals exceed 8 times the Tohoku signal, over a total of 1601, which leads to a statistical significance of p = 1 - 8/1601 ≈ 99%.

Computation of transient gravity signals associated with a seismic rupture

The deformation associated with earthquake processes induces a very large mass redistribution within the medium and a surface mass density anomaly associated with the uplift/subsidence of the ground [2]. We model an idealized seismometer as a mass contained in a housing attached to the Earth surface. Thus, the recorded signal is :

$$\boldsymbol{F} = \partial_t^2 \boldsymbol{s} + \boldsymbol{s}.\boldsymbol{\nabla\nabla}\phi^0 + \boldsymbol{\nabla}\phi^{E_1}$$

where the three terms are the inertial acceleration of the ground, the free air contribution and the gravity potential perturbation contribution.

Mode-sum representation of an acceleration response to a linear source function :

- for $t < t_{rupt}$:

$$\boldsymbol{a} = \sum_{modes} \frac{-i}{\nu} \frac{1}{t_{rupt}} \boldsymbol{\mathcal{A}} \left(e^{-\gamma t} e^{i\omega t}\right)$$

- for $t > t_{rupt}$:

$$\boldsymbol{a} = \sum_{modes} \boldsymbol{\mathcal{A}}\, e^{-\gamma t} e^{i\omega t}$$

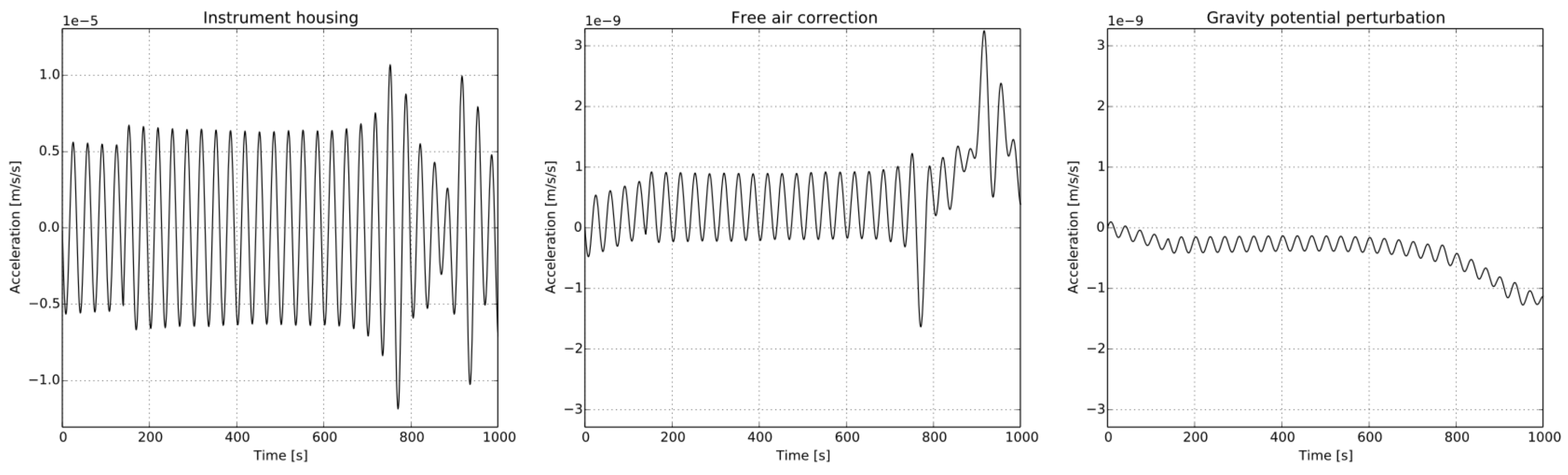

Figure 2 : Synthetics computed at the Virgo station (Italy) during the Tohoku event (Japan). The x-axis is in seconds after the earthquake origin time. A linear 140 seconds long moment-source function was used to model the Tohoku rupture.

Future work :
- We can observe a ringing phenomenon due to the truncation in the mode summation. Another approach will be studied [3,4], which enables to solve efficiently the elastodynamic equation at higher frequencies.
- Evaluate the consistency of the numerical simulations with analytical models [5], which suggests a t^3 evolution of the transient gravity signals.

Implications for earthquake early-warning systems (EEWS)

Current EEWS exploit information carried by P-waves. Our analysis shows that earthquakes can induce significant gravity perturbations at long distances : these perturbations travel much faster than seismic waves.

Potentials of gravity-based systems for the mitigation of earthquake and tsunami hazards:

- no delay due to P-wave travel time,
- increase the warning lead-times,
- very rapid estimation of earthquake source parameters,
- reduce the size of the *blind zone* (the zone around the hypocenter with no warning and most important damages).

Conclusions

Here we address the problem of detecting transient gravity signals from earthquakes during the fault rupture. We have shown the evidence of a signal associated to the Tohoku-oki earthquake, with a statistical significance of more than 99%.

We can constrain the shape of the transient gravity signals thanks to analytical formulations and numerical simulations. Work is under progress to unify these different approaches.

Since a dynamic gravity change should appear everywhere during the rupture, even before the arrival of seismic waves, a potential application of this study is the improvement of the performance of EEWS: reduction of warning times and blind zone size, rapid estimation of earthquake magnitude. New instruments more immune to seismic noise should be developed. Detection of gravity perturbations from fault rupture can open also new directions in seismology, since it consists in a direct measurement of the mass redistribution during the fault rupture.

Main references:

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