# Synchronized acoustic, optical and force sensors used to assess the dynamic of precursory events inside a destabilized grain packing


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## Objectives

When a grain packing is slowly tilted, precursory events of the grain destabilization can be detected at the free surface and inside the bulk by the use of optical [1], acoustic [2] and force measurements, respectively. The events are also associated to acoustic emissions that can be recorded by passive acoustics [3] and measured as pressure changes inside the bulk. The objective of the present work is better describing the dynamic of the precursors by triggering optical measurements with acoustic emissions at a high sampling rate and quantify time delays between surface and bulk measurements.

## Description of the multi-sensor experiments

Multi-sensor measurements, including optical, acoustic and force sensors, have been performed at the IPR laboratory on an experimental setup designed to study grain avalanches and precursory events [4]. A rectangular box (44, 20 and 18 cm in length, width and high, respectively) that contains glass beads (2 mm in diameter) is tilted at the rate of 0.055 °/s (quasi-static regime). Successive cycles from -24 to +24° and from +24 to -24° can be performed with one grain packing, allowing the acquisition and analysis of a large number of precursory events [4]. During the inclination, an optical camera takes successive pictures of the free surface (acquisition rate of 1 Hz), an acoustic transducer and a force sensor, which active faces are in contact with the beads, continuously record the ambient noise and pressure inside the bulk (sample rate of 5 kHz), 10 and 12.5 cm below the free surface, respectively (Figs. 1 a and b).

We highlight a periodic optical surface activitiy, which quantifies the amount of mobilized grains of a precursory event, that correlates with both acoustic emissions and pressure changes inside the bulk (Fig. 1c). The optical detections of the precursors are in advance to the detections performed inside the bulk, with time-delays lower than 1 second (Fig. 1d). To better highlight the difference between surface and bulk signatures of bead instabilities, a high-speed optical camera is used to record 8,188 pictures of the free surface at 2 kHz: the center of the recording time window is triggered by an amplitude threshold of the acoustic emission. As a preliminary approach, four precursory events detected at different tilt angles during the cycling experiment have been detailed for a single packing of 2 mm glass beads.


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[4] L. Oger, R. Delannay & Y. Le Gonidec, Powder and Grains (2021) https://doi.org/10.1051/epjconf/202124903023

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[6] J.-B. Legland, V. Tournat, O. Dazel & A. Novak, J. Acoust. Soc. Am., 131, 4292-4303 (2012)

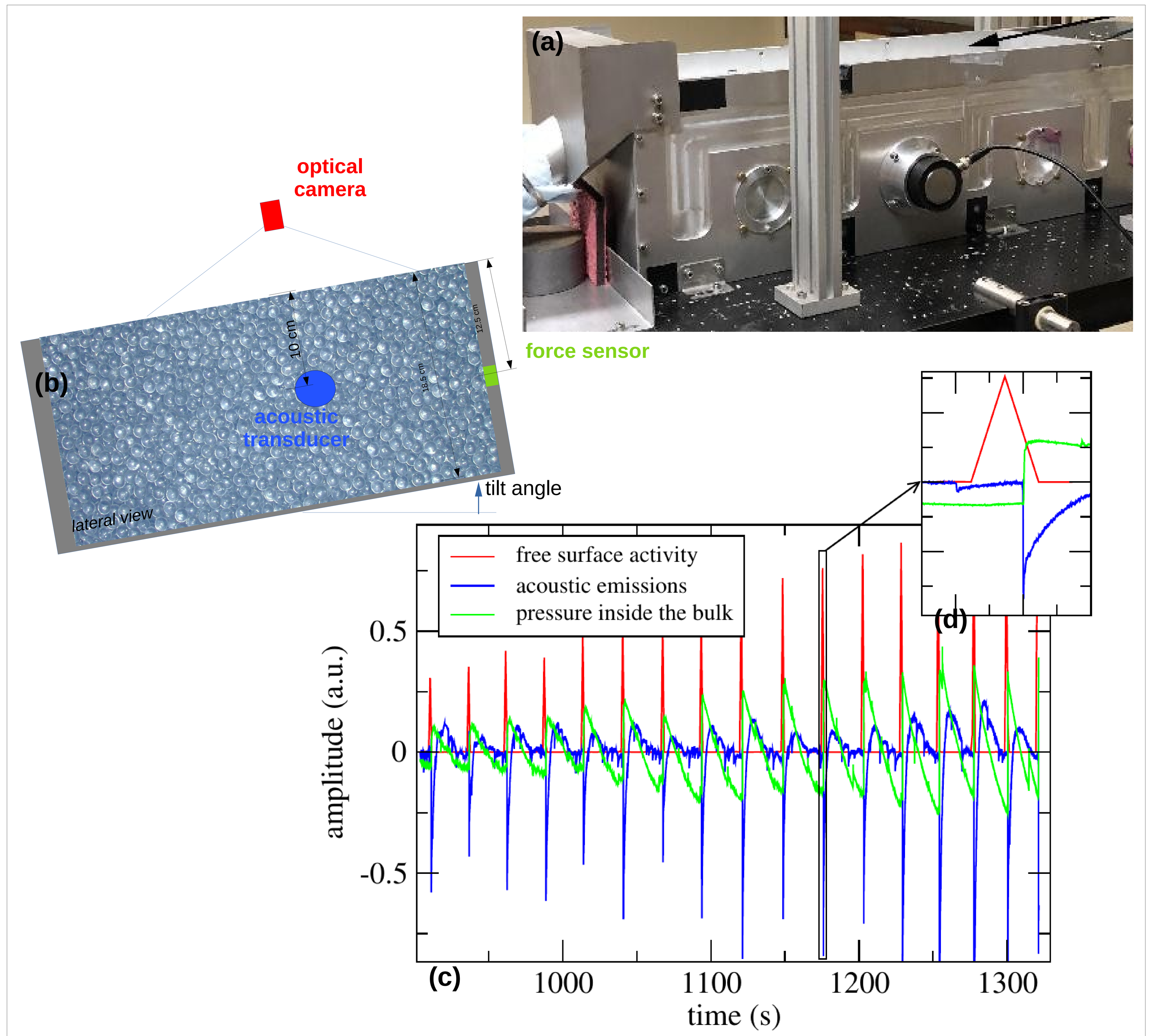




***Figure 1:***
*(a) experimental setup, box containing glass beads*
*(b) position of the sensors*
*(c) optical (red), acoustic (blue) and force (green) measurements performed during the inclination from 0° to 24°*
*(d) detail of the multi-sensor measurement associated to a precursory event*

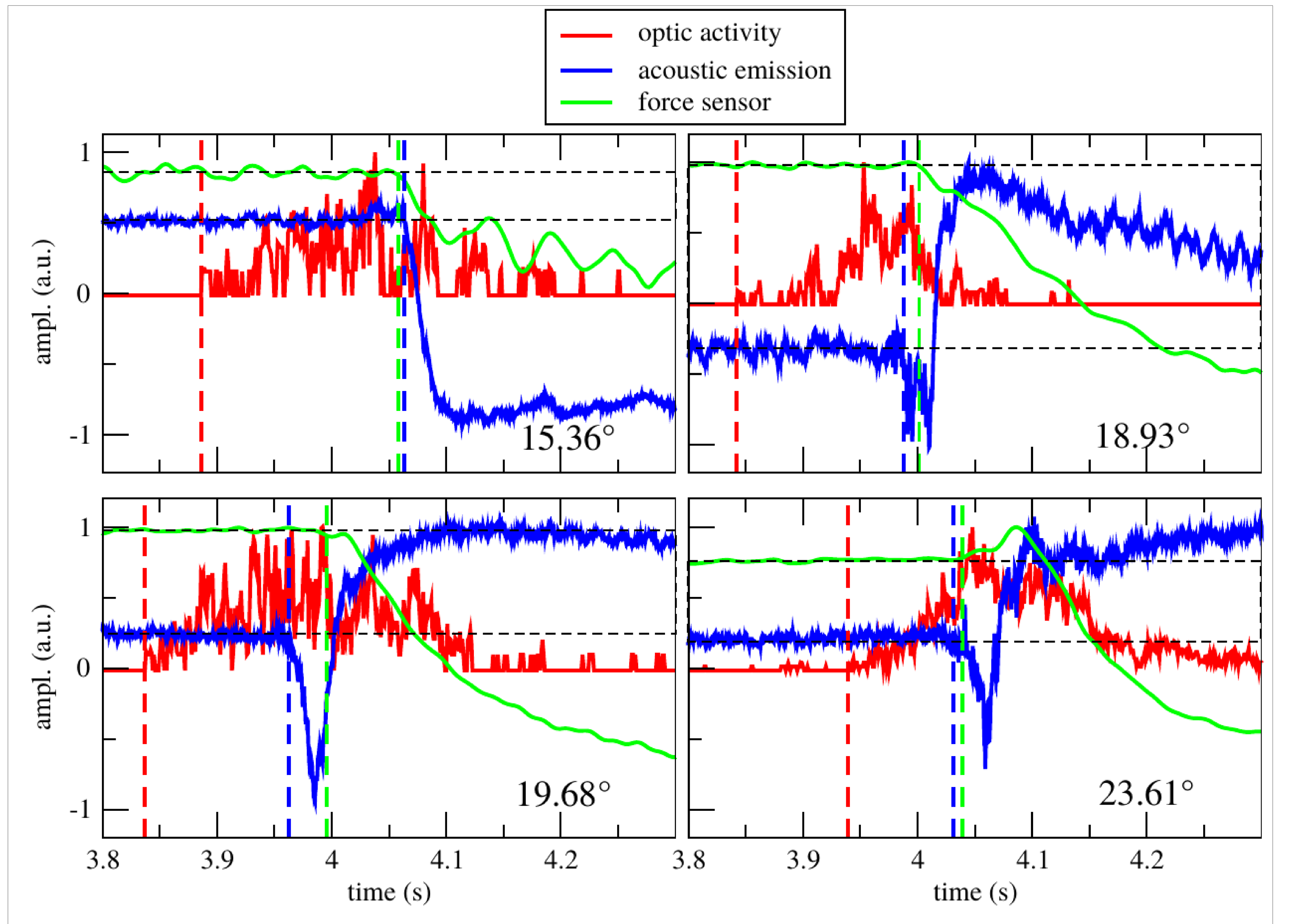
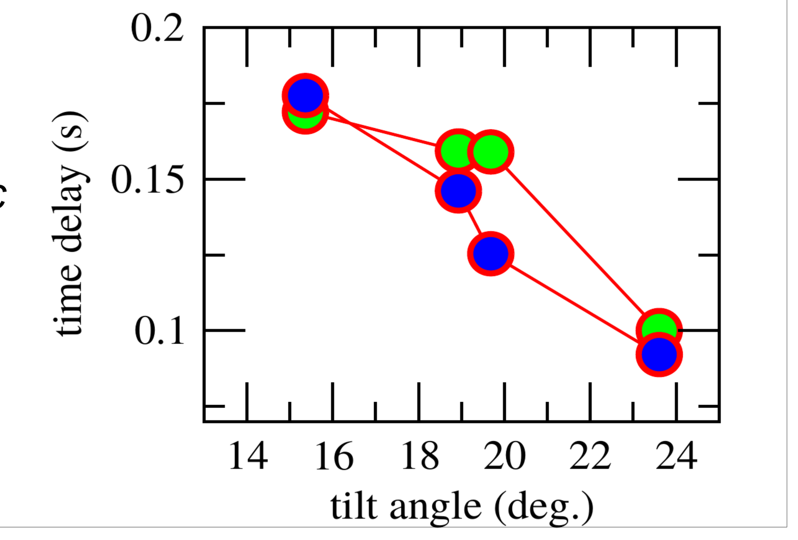



***Figure 2:*** *High-speed optical (red), acoustic (blue) and force (green) measurements during a precursory event with the associated starting times (dashed lines)*

***Figure 3:*** *Time-delays between optical-acoustic (blue dots) and optical-force (green dots) detection of precursory events detected at different tilt angles.*




## Analyses and interpretations

From the pre-triggered high-speed optical measurements of a precursory event, we highlight an abrupt increase of the surface activity which extends over about 400 ms (Fig. 2, red curves). In addition, the surface activity is detected with time-delays lower than 200 ms with both the acoustic emission and force decrease measured inside the bulk (Fig. 2, blue and green curves, respectively). The bead destabilization is not instantaneous but related to complex dynamic processes which look reproductive. We also show that the time-delay $\delta$ decreases with the tilt angle $\theta$ and as a first approximation, a linear relationship is given by $\delta = 0.34 - 0.01\,\theta$.

The dynamic of a precursor involves a microrupture event located inside the bulk at the depth z [5]: we show that this generates a pressure wave that propagates with a velocity $V=(H-z)/\delta$ inside the bulk, where H is the depth of the sensor. From the time-delays measured at four title angles $\theta$, the depth can be approximated by $z \approx 0.01V\,\theta - (0.34V - 0.1)$. By assuming a constant velocity V, this highlights that the depth of the microrupture linearly increases with the tilt angle, a behavior similar to $z \approx 0.018\,\theta - 0.252$ predicated by Amon *et al.* [5] for 2 mm glass beads. A quantitative agreement means a velocity V~1 m/s which is two orders of magnitude smaller than the sound velocity of a low frequency acoustic wave that mainly propagates through the solid skeleton of the bead packing [6].

## Conclusion

The present work presents preliminary results that quantify time-delays between optical, acoustic and force detections of precursory events at the free surface and inside the bulk of a grain packing. The precursor is related to a microstructure event that occurs at a depth that lineary increases with the tilt angle and generates a pressure wave that propagates at a velocity about 1 m/s inside the bead packing.