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Earthquake monitoring using volunteer smartphone-based sensor networks

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Abstract. *We introduce here the Earthquake Network project which implements a world-wide smartphone-based sensor network for the detection of earthquakes. Thanks to the accelerometric sensor, smartphones possibly detect the waves of a quake and report the event to a cloud computing infrastructure. In this work, we propose a solution to the detection problem based on statistical modelling the arrival times of the smartphone reports.*

Keywords. *Dynamic networks; Real time monitoring; Android; False alarms; Poisson process*

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1 Introduction

The Earthquake Network project (`http://www.earthquakenetwork.it/`) aims to develop a world-wide network of smartphones for real-time detection of earthquakes. The network is completely volunteer and it is based on the owners' smartphones. Each smartphone mounts an accelerometric sensor which, in principle, can measure the wave of a quake. In practice, smartphones are not fixed to the ground and they measure accelerations induced by a large number of sources. Nonetheless, the acceleration data collected by all the smartphones can be gathered together and analysed in order to distinguish real quakes from the "background noise". This is done through the Earthquake Network Android application (`https://play.google.com/store/apps/details?id=com.finazzi.distquake`) which, once installed, collects and sends the data to a cloud infrastructure for analysis. Since collection and data analysis are done in real-time, the earthquake is notified within few seconds from when it strikes. This should allow people living not too close to the epicentre to take measures before their area is affected. Secondly, a dense network of accelerometric sensors should help to provide high resolution shake-maps (maps of the ground acceleration) based on direct measurements. This paper discusses the data acquisition process and proposes a solution to the detection problem based on the statistical analysis of the smartphone reports. More details can be found in [1].

2 Data acquisition

Smartphones which take part to the Earthquake Network project collect accelerometric data only when they are charging (to avoid battery drainage) and when they are known to be fixed in space and not in use. If nothing is happening, the smartphone measures an acceleration equal to zero unless for a small error due to the electronic noise of the sensor circuits. A classic control chart is thus used to detect if the acceleration exceeds a threshold. When this happens, the event is reported to the cloud along with the spatial position of the smartphone and additional information on the event. The event is simply called a "vibration event" as it is not necessarily related to a quake. Each smartphone also reports its state to the cloud every 30 minutes. This allows to have an estimate of the number of smartphones that, at a given time, are enabled to detect vibrations and thus a possible quake.

3 Earthquake detection

Under normal circumstances, the cloud constantly receives vibration events from smartphones all over the world at random times. Indeed, a vibration event may be triggered by a large number of causes each one with a probability of occurrence much higher than the probability of a quake. However, when a quake strikes, it usually affects a relatively large area and thus a given number of smartphones at the same time. The idea, thus, is to detect a quake when, for a given area and at a given time, the instant rate of the vibration events exceeds a threshold. In order to simplify the discussion, we consider here a fixed spatial area (e.g. a city or a small region) and we assume that, when a quake occurs, the entire area is affected.

Let $\{N(t), t > t_0\}$ be the stochastic point process describing the arrival time of the vibration events which is assumed to be a Poisson process with conditional intensity function $\mu(t)$. To define $\mu(t)$, we consider the number of enabled smartphones at time t, namely n_t. Although this quantity is not directly observed at time t, we observe the number of enabled smartphones sending their "I am alive" signal in the interval $(t - 30\ min, t]$, say ν_t. Hence, n_t can be assumed to be a conditionally independent random variable with distribution parametrized by ν_t and some additional covariates denoted by x_t. In particular, we assume n_t to be conditionally Poisson distributed with expectation

$$E(n_t|\nu_t) = \nu_t \exp\left(\beta' x_t\right).$$

Henceforth, the conditional intensity of $N(t)$ is given by

$$E(N(dt)|\mathfrak{H}_t) = \mu(t)\,dt$$

where $\mathfrak{H}_t$ is the history up to time t and $\mu(t) = \alpha n_t$. Using this model we aim at detecting the occurrence of a seismic event as soon as possible. To do this we observe that there is a delay in signal transmission and seismic wave displaced perception and we consider the vibration signals in the interval $I_\tau^t = (t - \tau, t]$, for some $\tau > 0$, as signals related to the same earthquake. Extending change point detection techniques which are tailored for permanent changes and asymptotic theory, we consider here $N_\tau^t = N(I_\tau^t)$ signals and two likelihood approaches based respectively on the generalized likelihood ratio (GLR) statistic and the efficient score. In order to develop the above mentioned likelihood detectors, the well known log-likelihood of the signals in the interval I_τ^t is introduced

$$\log L(\mu|t,\tau) = \sum_{t_j \in I_\tau^t} \log \mu(t_j) - \mu\left(I_\tau^t\right).$$

where t_j are the arrival times of the events in I_τ^t. Now suppose that, in absence of earthquakes, the process intensity is $\mu^0(t)$ while under a seismic event the process intensity is

$$\mu(t) = \mu^0(t) + \frac{\lambda}{\tau}$$

with $\lambda > 0$ for $t \in I_\tau^t$ and $\lambda = 0$ otherwise. The above log-likelihood has thus the following form

$$\log L(\lambda) = \sum_{t_j \in I_\tau^t} \log\left(\mu^0(t_j) + \frac{\lambda}{\tau}\right) - \mu^0\left(I_\tau^t\right) - \lambda$$

and for a fixed τ, the GLR statistic is given by

$$GLR(\tau,t) = \sum_{t_j \in I_\tau^t} \log\left(1 + \frac{\hat{\lambda}_\tau^t}{\tau\mu^0(t_j)}\right) - \hat{\lambda}_\tau^t$$

where $\hat{\lambda}_\tau^t = \max\left(0, \arg\max_{\lambda} L(\lambda)\right)$. Note that the above GLR gives an earthquake warning if

$$\sup_{\tau>0} GLR(\tau,t) > h$$

for some threshold h. In particular, since $\mu^0(t)$ depends on n_t, we replace it by its expectation $E\left(\mu^0(t)|\nu_t\right) = \alpha\nu_t \exp(\beta' x_t)$. The second likelihood approach is based on the efficient score which is given by

$$S(\tau,t) = \frac{\partial}{\partial\lambda} \log L(\lambda)\bigg|_{\lambda=0} = \sum_{t_j \in I_\tau^t} \frac{1}{\tau\mu^0(t_j)} - 1$$

and the score detector gives an earthquake warning if $\sup_{\tau>0} S(\tau,t) > h$ for some threshold h, where μ^0 is defined as above.

4 Network expansion

The Earthquake Network project was open to the general public on January 2013. 17 months later, the Android application has been downloaded more than 320′000 times and it is currently installed on around 50′000 Android devices all over the world. At any given time, only a small fraction of smartphones (between 3% and 12% according to the time of day) are enabled to detect a quake so the number of installations is not as large as it seems and the network has ample room for growth. As the network is volunteer, the Earthquake Network project is more popular in seismic countries. Mexico holds 48% of the total downloads followed by Chile (20%) and Italy (12%). The current state of the network can be seen at `http://earthquakenetwork.it/?page_id=17` . The image of Figure 1 shows the trend of the number of smartphones with the Earthquake Network Android application during the last 6 months. Note that the trend is not necessarily monotone as the user can leave the network at any time. As an example, the image of Figure 2 shows the spatial distribution of the smartphones installing the Earthquake Network application in Mexico City at a given time. Till now, the network has detected around 40 quakes mostly above local magnitude 5.0. Milder quakes are more difficult to detect as they usually affect smaller areas and not all smartphones in the area might detect them. A denser network and/or a higher number of enabled smartphones, however, should allow to detect earthquakes starting from magnitude 3.0. In any case, the Earthquake Network project does not aim to replace the "official" seismic networks but is intended to generate early warnings in the case of strong quakes that may be dangerous for the population.

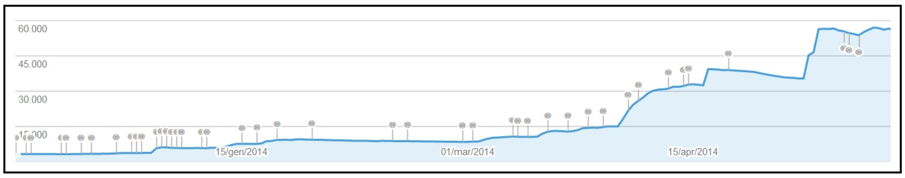

Figure 1: Number of smartphones with the Earthquake Network application during the last 6 months.

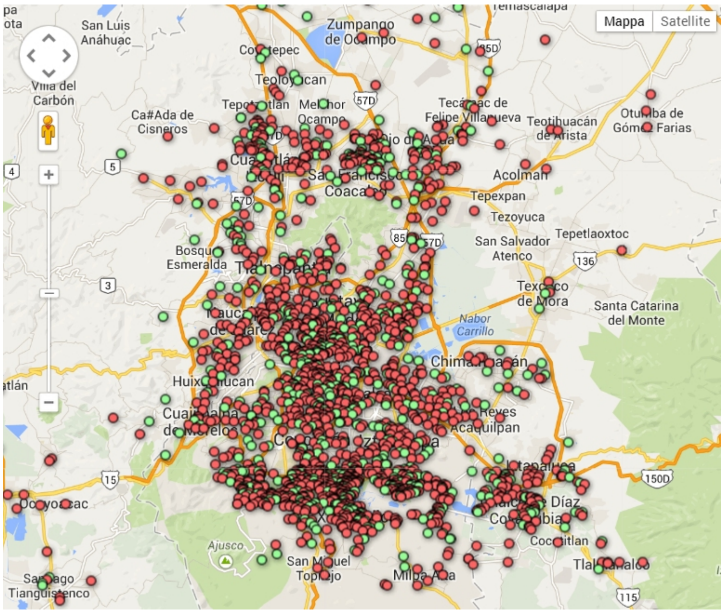

Figure 2: Spatial distribution of the smartphones in Mexico City (June 3^{rd}, 2014 10:00 UTC). Red dots: active smartphones; green dots: smartphones enabled to detect earthquakes.

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References

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