An Adaptive, Mobile, Community-deployed Network of Low Cost Air Pollution Sensors for a City in the Developing World

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Abstract: Many cities in developing countries have dangerously high levels of air pollution, often with little or no regular monitoring. Recently, small, low-cost and low-power particulate monitoring tools have become available. We propose to deploy a distributed network of sensors mounted on motorbike taxis. To optimise the spatial and temporal coverage of the city we will use an innovative incentive based system, to encourage the drivers to sample those times and places with the greatest uncertainity. Combining this with static monitoring stations and high precision calibration, we aim to map the particulate pollution across Kampala, and develop affordable tools which could be applied in other low-income countries.

Keywords: machine learning, market, geo/maps, public health, air pollution, urbanisation.

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1. PROPOSAL

Rapid economic development, combined with poor regulatory controls has meant many cities in developing countries have almost continuous levels of dangerous air pollution, contributing to over three million deaths in 2012 [WHO 2014a]. The WHO however note a severe lack of data on air pollution in some regions (Fig. 1), in particular in East Africa [WHO 2014b].

Most air pollution monitoring systems have been developed for cities in middle and high income countries, where many monitoring stations can be installed across cities and the results from similar cities can be used to infer pollution dispersion. In Kampala, as in other cities of low-income countries, the source distribution may be different (for example the burning of rubbish, the use of solid fuels for cooking, the use of emergency generators and the dust generated from unpaved roads), and the dispersal pattern may differ. In particular the absence of applied models for developing countries [Hoek et al. 2008], is a considerable gap in the literature. The lack of information around the source and distribution of pollution makes intervention inefficient and makes it impossible to evaluate, making it difficult to motivate and implement mitigation programs.

In Kampala, a city of almost two million people, no regular monitoring of air pollution is taking place [WHO 2014a], with just one passive sample [Schwander et al. 2014] reported in the literature. Until recently, continuous automatic air pollution monitoring required very expensive and complex devices [Schwela 2011]. In a low-income country such as Uganda, such equipment is impractical. Recently however, a series of low cost automatic PM2.5 air pollution monitoring systems have become available. Studies have already started the process of testing and calibrating these devices [Holstius et al. 2014; Morpurgo et al. 2012; AQICN 2013], with promising results.

Besides their low cost and simplicity, these devices have the added advantage of being extremely small and low-power, offering the opportunity for mobile data collection. A couple of small scale attempts have been tested in developed countries [Ma et al. 2008; Dutta et al. 2009], some are dependent on volunteers wearing or carrying the devices around their city[MFC 2014]. No incentive was provided to ensure a good distribution of data and the trial results have not yet been published, the experiments were short-lived due to the high costs of the devices used and the effort required from the volunteers involved.

This project would consist of two monitoring programs; First, a static network of low-cost PM2.5 sensors would be deployed across Kampala, covering different land-use and topographical regions. Combined with these, manual recording using an on-loan reference device would allow the values from the sensors to be calibrated and confidence intervals estimated. Second, the same type of sensors will be mounted on motorbike taxis (known locally as bodas). Powered by the bike's battery the device would report both the level of PM2.5 and

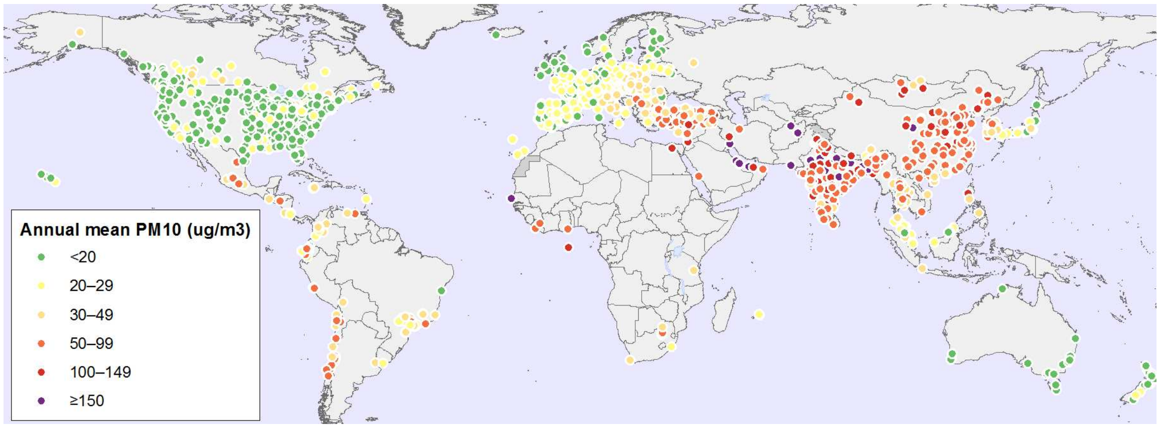

Fig. 1. Map from the WHO showing urban PM10 air pollution (averaged between 2008-2013), illustrating the paucity of data from East Africa. Image from http://gamapserver.who.int/mapLibrary

its coordinates. A similar, but high-cost, scheme has been deployed in Zurich, Switzerland [Li et al. 2012]. However this network of sensors was restricted to the routes on the city's tram network, giving an incomplete and potentially bias picture of the city's air quality. The bodas in Kampala are renown for being able to go almost anywhere, including along off-road tracks and through informal settlements.

To improve the spatial sampling across the city, the boda drivers will be offered financial incentives dependant on where in the city they visit, with the incentives chosen to optimise the estimates of the pollution distribution. The payment information will be distributed via text instructions to the boda driver's own mobile phones.

Technical plan

Our proposed technical plan is comprised of the following:

(1) Validate the low-cost pollution sensor in the field (already in progress).
(2) Develop a model of pollution using real-time data from the bodas, to provide estimates of pollution and to provide the locations of greatest uncertainty towards which the incentive scheme will direct the bodas.
(3) Develop an automated system of payments to communicate and reimburse the bodas.
(4) Assess whether an improvement in spatial distribution is achieved with the variable payment system.
(5) Assess the accuracy of the pollution estimates by using the fixed pollution sensors and calibration data.

The parameters for the incentive scheme will adapt depending on the market cost of the boda's participation and on the utility of the potential data, which will depend not only on the frequency of sampling in an area but the heterogeneity of the pollution in that location. A possible method would be to use a coregionalised Gaussian process in which land use and pollution are the two output variables, for example Li et al. [2014], to provide estimates of the level of pollution and its uncertainty for a given time and location. Those times and locations with the greatest uncertainty will have the greatest rewards for the boda drivers, providing the greatest reduction in uncertainty for the least cost, possibly based on a model such as Li and Faltings [2012]. Such a model could be used for other applications where repeated sampling from large coregionalised spatio-temporal maps is required (e.g. other environmental pollutants, monitoring crop yield and disease or human health).

As a pilot, a Shinyei PPD42NS PM2.5 particulate sensor has been connected to the mic input of an android phone (Fig. 2). An app has been developed which processes the Shinyei's output and uploads this data to a website[1], handling network outages by caching samples until the connection is restored. The phone and sensor are powered by a solar panel and battery system developed for another ongoing project [Quinn and Nakibuule 2012], mounted near the entrance to Makerere University.

Expected outcomes

The principle outputs of the project are; a low cost method to determine Kampala's baseline pollution level and a spatial map highlighting hot-spots where PM2.5 are particularly concentrated, using an innovative incentive based method for sensor deployment.

[1] The real-time, raw Shinyei data from the current testing period is available at `https://thingspeak.com/channels/15326`

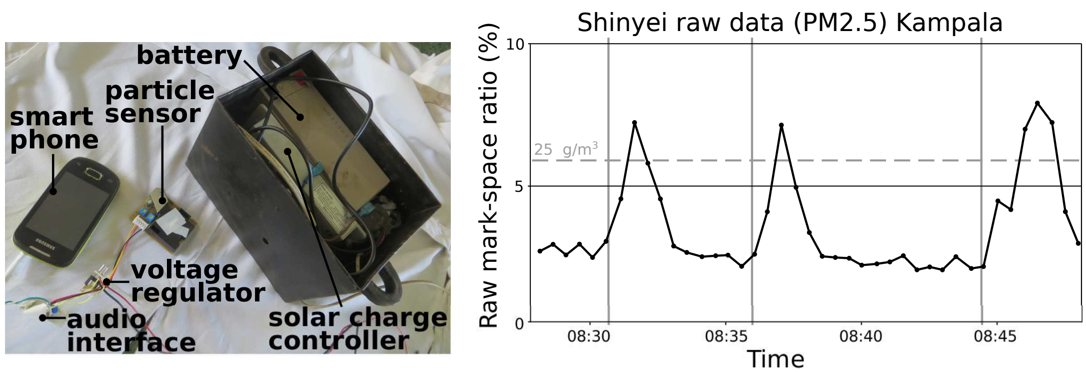

Fig. 2. Left: Partly dismantled prototype air pollution sensor. Right: Raw test data from a less polluted part of Kampala. Matches were lit in the vicinity of the sensor at the times marked by the three vertical lines. For illustration, the approximate location of the $25\mu g/m^3$ threshold is also included, indicating the EU's average annual target.

The academic outputs include, first, validation of models of pollution dispersion, such as Kakosimos et al. [2010] and Hoek et al. [2008], for an East African city. Second, a method for distributing a financial incentive in a way which minimises uncertainty in a spatio-temporal variable. Third, the pollution estimates will be highly useful academically (for example in confirming hypotheses regarding the prevalence of pollution-related-diseases). Fourth, develop 'backward-reasoning' models to identify the causes of the pollution.

REFERENCES

AQICN. 2013. Dylos Air Particule[sic] Counter Experimentation. aqicn.org/faq/2013-09-08.

Dutta, P. et al. 2009. Common sense: participatory urban sensing using a network of handheld air quality monitors. In *Proceedings of the 7th ACM conference on embedded networked sensor systems.* ACM, 349–350.

Hoek, G. et al. 2008. A review of land-use regression models to assess spatial variation of outdoor air pollution. *Atm. Env.* 33, 7561–78.

Holstius, D. et al. 2014. Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California. *Atmospheric Measurement Techniques Discussions 7,* 1, 605–632.

Kakosimos, K. E. et al. 2010. Operational Street Pollution Model (OSPM)–a review of performed application and validation studies, and future prospects. *Environmental Chemistry 7,* 6, 485–503.

Li, J. J. et al. 2012. Sensing the Air We Breathe-The OpenSense Zurich Dataset. In *AAAI.*

Li, J. J. et al. 2014. Estimating Urban Ultrafine Particle Distributions with Gaussian Process Models. *R@Locate14*, 145–153.

Li, J. J. and Faltings, B. 2012. Incentive schemes for community sensing. In *The 3rd Intl. Conf. in Computational Sust.*

Ma, Y. et al. 2008. Air pollution monitoring and mining based on sensor grid in London. *Sensors 8,* 6, 3601–3623.

MFC. 2014. Pepys Air Quality, Mapping For Change. www.mappingforchange.org.uk.

Morpurgo, A. et al. 2012. A low-cost instrument for environmental particulate analysis based on optical scattering. In *Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International.* IEEE, 2646–2650.

Quinn, J. and Nakibuule, R. 2012. AI-DEV: Artificial Intelligence in the Developing World. aidevmakerere.blogspot.com.

Schwander, S. et al. 2014. Ambient particulate matter air pollution in Mpererwe district, Kampala:A pilot study. *Jn of env.&pub. health.*

Schwela, D. 2011. *GAP Forum Air Pollution Monitoring Manual.* Global Atmospheric Pollution Forum.

WHO. 2014a. Ambient (outdoor) air pollution in cities database 2014. www.who.int/phe/health_topics/outdoorair.

WHO. 2014b. News release: Air quality deteriorating in many of the worlds cities. www.who.int/mediacentre/news/releases.

2. DATA POLICY

All code produced during the study is to be made publicly available through a git repository. The analysis of results will be made available through open-access publications and pollution maps. The raw and preprocessed data from the fixed monitoring stations will be made available in real-time through an internet-of-things website. The data from the mobile sources will be released after a short delay (to ensure participant anonymity).

3. BUDGET

Item	Amount (USD)
Graduate student stipend (1 year @ 100%) + tuition	28000
Student conference travel	2500
Total	**30500**

The project has other costs associated (the sensor hardware and the payment to participants), but we aim to cover these from the current departmental research budget. We are also applying for funding for additional hardware, to improve our calibration and test capabilities.