Surface Pressure Observations from Smartphones:
A Potential Revolution for High-Resolution Weather Prediction?

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**Capsule Description:** Pressure observations from smartphones have the potential to provide millions of observations per hour that could revolutionize high-resolution weather prediction.

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Abstract

Millions of smartphones now possess relatively accurate pressure sensors and the expectation is that these numbers will grow into the hundreds of millions globally during the next few years. The availability of millions of pressure observations each hour over the U.S. has major implications for high-resolution numerical weather prediction. This paper reviews smartphone pressure sensor technology, describes commercial efforts to collect the data in real time, examines the implications for mesoscale weather prediction, and provides an example of assimilating smartphone pressure observations for a strong convective event over eastern Washington State.
Introduction

During the past few years, tens of millions of smartphones with relatively accurate pressure sensors have been sold throughout the world, with the goal of providing information for internal navigation within buildings and better altimetry, among other uses. A smartphone is defined here as a mobile phone with substantial computational ability, a high-resolution screen, and wifi and gps capabilities, in addition to the phone and text capabilities of standard cellular phones. Smartphones are capable of running a wide variety of applications (apps) and are available with a number of operating systems (e.g., Apple iOS, Google Android, Windows mobile). By 2016, industry sources (HIS, isuppli.com) expect that between 500 million and one billion smartphones and tablets will have the capacity to measure pressure as well as parameters such as position, humidity, and temperature. Ultra-dense networks of pressure observations provided by smartphones and other portable platforms could contribute detailed information describing mesoscale phenomena such as convective cold pools, mountain waves, fronts, and others. This paper will examine the potential of such massive numbers of surface observations to greatly improve our ability to describe and forecast the three-dimensional structure at the atmosphere, potentially leading to revolutionary improvements in high-resolution numerical weather prediction.

Why is surface pressure so special?

Pressure is perhaps the most valuable surface meteorological variable observed regularly. Unlike surface air temperature and humidity, surface pressure reflects the deep structure of the overlying atmosphere. Surface pressure has fewer of the observational problems that plague surface wind, temperature and humidity; unlike wind and temperature, pressure can be measured
inside or outside of a building, in or out of the shade, and is not seriously impacted by
downstream obstacles or urbanization. Surface pressure is not influenced by the characteristics
of the underlying surface, as are temperature and wind. Although surface pressure
measurements can have systematic biases like other surface variables, pressure biases for a static
sensor are generally unchanging (perhaps due to poor elevation information or calibration) and
thus can be easily removed by straightforward quality control algorithms.

Several recent studies, most using ensemble-based data assimilation systems, have
demonstrated that surface pressure provides considerable information about three-dimensional
atmospheric structures. Ensemble-based data assimilation systems are particularly adept in
getting maximum value from surface pressure information; such systems produce flow-
dependent background error covariances, build covariances based on the natural atmospheric
structures in the model, and allow impacts for pressure on all other model variables throughout
the atmospheric volume. On the synoptic scale, Whitaker et al. (2004) showed that a limited
number of global surface pressure observations could produce a highly realistic 20th-century
reanalysis that closely resembled the analysis produced by the full collection of observing assets
during a comparison period encompassing the later part of the century. Using regional
assimilation of pressure observations from airport locations, Dirren et al. (2007) was able to
reproduce synoptic-scale upper-air patterns over western North America and the eastern Pacific.

Although less work has been completed on the assimilation of surface pressure
observations on the mesoscale, early investigations have been promising. Wheatley and
Stensrud (2010) investigated the impacts of assimilating both surface pressure and one-hour
pressure change for two convective events over the U.S. Midwest. Using a relatively coarse
model resolution (30 km) and only assimilating airport ASOS (Automated Surface Observing
System) observations, they found that surface pressure observations facilitated accurate
depictions of the mesoscale pressure patterns associated with convective systems. More
recently, Madaus et al. (2013) found that ensemble-based data assimilation of dense pressure
observations can produce improved high-resolution (4-km) analyses and short-term forecasts that
better resolve features such as fronts and convection. Considering the apparent promise of
surface pressure observations for improving analyses and forecasts, the next step is to evaluate
this potential by applying state-of-the-art data assimilation approaches to a pressure observation
network enhanced with conventional observations and pressure data available from new
observing platforms such as smartphones.

Increasing availability of fixed surface pressure observations

During the past decades there has been an explosion in the availability of surface pressure
observations across the U.S. A quarter century ago, surface pressure observations were limited
to approximately 1000 airport locations across the country. Today, these ASOS sites are joined
by hundreds of networks run by utilities, air quality agencies, departments of transportation and
others, plus public volunteer networks such as the Weather Underground and the Citizen
Weather Observer Program (CWOP)\(^2\). By combining these networks, tens of thousands of
surface pressure observations are collected each hour across the U.S. Over the Pacific
Northwest region, encompassing mainly Washington, Oregon, and Idaho, roughly 1800 pressure
observations are currently collected each hour from approximately 70 networks (Figure 1 from
Madaus et al., 2013), compared to approximately 100 ASOS locations. As shown in that figure,
even when large numbers of networks are combined, substantial areas, particularly in rural
locations, have few pressure observations, and many observation locations only report once an

\(^2\) http://wxqa.com/
hour. Fortunately, an approach for increasing radically the number and temporal frequency of surface pressure observations exists: the use of pressures from smartphones and other portable digital devices.

### Smartphone Pressure Observations

During the past two years a number of smartphone vendors have added pressure sensors, predominantly to Android-based phones and tablets/pads. The main reason for installing these pressure sensors was to identify the building floor on which the device is located or to aid in vertical altimetry. Samsung began using pressure sensors in its popular Galaxy S III smartphone in 2012 and such sensors have remained in the Galaxy S IV released in 2013 (Figure 2). Pressure sensors are also available in other Android phones and pads, including the Galaxy Nexus 4 and 10, Galaxy Note, Xoom, RAZR MAXX HD, Xiaomi MI-2 and the Droid Ultra. According to industry analyst IHS Electronics and Media (isuppli.com), approximately 80 million pressure-capable Android devices were sold in 2012, with expectations of 160 and 325 million units for 2013 and 2014, respectively. By 2015, isuppli.com estimates that well over a half-billion portable devices worldwide will have the capability for real-time pressure observation, including over 200 million in North America. There is the strong expectation that non-Android device vendors such as Apple will include pressure sensors in upcoming smartphones and tablets. **Thus, the potential may exist to increase the number of hourly pressure observations over the United States by roughly 10,000 times over the current availability from current networks.**

Some insight into the potential availability and distribution of smartphone pressures is available from a map of the current U.S. coverage for the largest American cell phone network,
Verizon (Figure 3). Nearly all of the eastern two-thirds of the lower 48-states is covered, encompassing nearly the entire range of U.S. severe convective storms. Coverage over the western U.S. has gaps over the highest terrain and sparsely populated desert areas, but is still extensive (covering perhaps 65% of the land area) and includes all the major West Coast population centers from Seattle to San Diego. Coverage over the Interstate Highway system is particularly good, even over less populated rural areas. The number of smartphone observations will undoubtedly be dependent on population density, with the largest over the eastern U.S. and the West Coast.

The accuracy and resolution of the pressure sensors in smartphones and tablets are surprisingly good. Many of the current Android devices use the ST Microelectronics LPS331 MEMS pressure sensor, which has a relative accuracy of +/-.2 hPa, an absolute accuracy of +/−2.6 hPa, and includes temperature compensation\(^3\). Such relative accuracy allows accurate determination of pressure change, the use of which is discussed later in this paper.

The potential for large numbers of smartphone pressure observations has attracted several application developers that have created Android apps that collect smartphone pressures and positions (through GPS or cell tower triangulation). One firm, Cumulonimbus, has developed the pressureNet app for Android phones and tablets (http://www.cumulonimbus.ca/). Smartphone owners must download the pressureNet app to allow their pressures to be reported; however, with the insertion of the pressureNet code into popular apps, it is expected that the number of smartphone pressures collected by Cumulonimbus will increase by one or two orders of magnitude during the next year. Currently, they are collecting tens of thousands of surface

pressure observations globally each hour and have made them available to the research
community and others. Another group collecting pressure observations on Android phones is
OpenSignal (http://opensignal.com/), whose application of the same name collects smartphone
pressure observations, other meteorological parameters (temperature, humidity, and light levels),
and wifi/cell phone signal levels. They have also developed an app, called WeatherSignal, that
displays the meteorological observations provided by a phone. A plot of the pressureNet and
OpenSignal observations at one time (1900 UTC October 30, 2013) over North America is
shown in Figure 4. Although only about 27,000 smartphone pressure observations are available
today across the U.S. through the pressureNet app and OpenSignal apps, a small number
compared to the millions of phones with pressure capabilities, there are still regions, such as the
northeast U.S., with substantial smartphone observation densities that greatly enhance current
observation networks.

Motor vehicles offer another potential platform for acquiring high-density pressure
observations. Solid-state atmospheric pressure sensors are found in most cars and trucks, which
also possesses ambient temperature sensors for use in engine management computers (Mahoney
et al., 2013). The main challenges for use of vehicle pressure observations are position
determination (easily dealt with by GPS), real-time communication, and privacy issues. A
number of auto industry analysts (e.g., Machina 20134) predict that most cars will have Internet
connectivity by 2020.

**Other smartphone weather observing capabilities**

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4 https://m2m.telefonica.com/m2m-media/m2m-downloads/detail/doc_details/530-connected-car-report-2013#530-Connected%20Car%20Report%202013-english
Some smartphones, such as the Samsung Galaxy IV, have the capability to measure other environmental parameters such as battery temperature, humidity, magnetic field, and lighting intensity. Temperature and humidity measurements from smartphones are of far less value than pressure, since the dominant influence of the immediate environment (inside of a pocket or a building) produces readings that are unrepresentative of the conditions in the free air. However, a recent study found that with statistical training and correction using observed temperatures, large numbers of smartphone temperatures can be calibrated to provide useful measures of daily average air temperatures over major cities (Overeem et al., 2013). Related work has shown that the attenuation of the microwave signals between cell towers is sensitive to precipitation intensity, and that such information can be used to create precipitation maps that closely resemble radar reflectivity (Overeem et al., 2013b).

**Challenges in using smartphone pressure observations**

The value of smartphone pressures in support of numerical weather prediction can be greatly enhanced with proper calibration, pre-processing, and preselection. Gross range checks can reject clearly erroneous pressures. Either pressure or pressure change can be assimilated by modern data assimilation systems. For pressure-change assimilation, only smartphones that are not moving should be used, something that can be determined from the GPS position and observed pressures from the phones (vertical movement will generally produce far more rapid pressure variations than meteorological changes).

The elevation of the smartphone is required to assimilate either pressure or pressure change. GPS elevations are available, but can have modest errors (typically +/−10 meters, roughly equivalent to a 1 hPa pressure error, the typical error variance used in most operational
If one has a collection of pressures in an area, it might reasonable to assume that the highest pressures reflect values on the first floor of residences or in a vehicle, representing pressure at roughly 1-m above ground elevation. Since it makes little sense to assimilate pressure observations in regions where models lack sufficient resolution to duplicate observed pressure features, pressure observations in such areas should be rejected when model and actual terrain are substantially different (Madaus et al. 2013). Clearly, some experimentation will be required for developing algorithms that derive maximum value from smartphone pressures.

**What kind of weather forecasts could smartphone pressures help the most?**

Although an ultra-dense network of smartphone pressure observations would undoubtedly positively impact general weather prediction, there are several phenomena for which they might be particularly useful. One major problem is forecasting the initiation of severe convection, with models being initialized before any precipitation or radar echo is apparent. At such an early stage of development, subtle troughs, dry lines, convergence lines, and remnants of past cold pools can supply major clues about potential convective development, information that dense collections of smartphone pressures might well be able to provide. The example in the next section of this paper illustrates the value of even a modest density of smartphone pressures for simulating a strong convective event. Forecasting the positions of fronts and major troughs, even a few hours in advance, can have large value for wind energy prediction since such features often are associated with sudden rapid ramp ups and ramp downs in wind energy generation. As shown by Madaus et al. (2013) the assimilation of dense

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5 A discussion of the vertical errors in GPS-based elevation is found at [http://gpsinformation.net/main/altitude.htm](http://gpsinformation.net/main/altitude.htm).
pressure observations can shift fronts in a realistic way that substantially improves short-term wind forecasts. High-resolution pressure observations from smartphones might also aid in the initialization and monitoring of mesoscale troughing associated with downslope winds and leeside convergence zones. Dense pressure observations along coastlines could provide significant information regarding approaching weather features, including the positions of offshore low centers and fronts.

Even the densest portions of the U.S. surface observation network are generally too coarse to observe and initialize features on the meso-gamma (2-20 km) and smaller scales. Smartphone pressure observations may offer sufficient data to do so, particularly over the smartphone-rich regions of the eastern U.S. and West Coast. An interesting advantage of smartphone pressure observations is that they could be easily added in any location where power and cell-phone coverage is available.

An example of assimilating smartphone pressures

Although the smartphone pressure acquisition is still at an early stage, with observation densities orders of magnitude less than what will be available in a few years, it is of interest to try some initial assimilation experiments to judge the impacts of even modest numbers of smartphone pressures. To complete such a test, smartphone observations made available by Cumulonimbus were used to simulate an active convective event over the eastern slopes of the Washington Cascades that brought heavy showers and several lightning-initiated wildfires. For this experiment, an ensemble-Kalman filter (EnKF) data assimilation system, adapted from one provided by the UCAR Data Assimilation and Research Testbed (DART) program, was applied at 4-km grid spacing and used the Weather Research and Forecasting (WRF) model, V3.1. The
ensembles (64 members) for these experiments were cycled every three hours from 1200 UTC 29 June through 1200 UTC 30 June 2013. The impacts of smartphone pressures were examined for a three-hour period ending on 0300 UTC 30 June 2013.

Figure 5 shows both the surface pressures provided by the conventional ASOS network (metar, blue squares) and the smartphone pressures (pnet, red dots) available at 0000 UTC 30 June 2013. A number of smartphone pressures were available over the eastern slopes of the Cascades, the region of strongest convection. The accumulated rainfall estimated using the Pendleton, Oregon National Weather Service radar (PDT) for the three hours ending at 0300 UTC 30 June (Figure 6) shows substantial accumulation (up to approximately 32 mm) from intense convective cells. The University of Washington runs a real-time ensemble Kalman filter data assimilation system (RTENKF) that uses conventional surface observations, radiosondes, ACARS aircraft observations, and satellite-based cloud/water vapor track winds (Torn and Hakim 2008). This system, run on a three-hour update cycle, produced three-hour precipitation totals shown in Figure 6. This modeling system did produce some convective showers over and to the east of the Cascades, but failed to duplicate the intensity of the lee-side showers and had considerable spread in convective locations. Figure 6 shows the result of adding the smartphone pressure observations (Figure 5) to the mix of observations used in the RTENKF system. With the added pressure observations, the ensemble system produced far more intense convective cells east of the Cascade crest, with some with orientations and magnitudes more reminiscent of the observed than provided by the RTENKF system. In addition, more ensemble members were near the observed location of the most intense convection (Figure 7). This, of course, represents only one case, but suggests that assimilating smartphone pressures can both change and enhance
short-term mesoscale forecasts. It is reasonable to expect that further increases in the number of
pressure observations would provide additional improvements in convective and other forecasts.

**Looking towards the future**

During the next few years, the number of smartphones/tablets with pressure sensors
should increase into the tens of millions over North America and the hundreds of millions
globally. If private sector firms or other organizations can develop the infrastructure to “harvest”
and share these pressure observations in real time, there could be a substantial improvements in
the quality of the initializations of high-resolution numerical weather prediction models and their
subsequent forecasts for a wide range of important weather features such as severe convection.
Initial research on the impacts of networks of surface pressure observations on mesoscale
prediction (e.g., Wheatley and Stensrud 2010, Madaus et al. 2013) suggest that ensemble-based
mesoscale data assimilation may offer an attractive approach to securing maximum benefit from
smartphone and other pressure observations, but considerably more testing and experimentation
is needed, including understanding the relative value of pressure and pressure change
assimilation. Furthermore, better approaches for quality control and bias correction of
smartphone pressures can enhance the value of these new observation sources. During the next
decade a large number of pressure observations from vehicles will likely join the current
smartphone collection as transportation platforms gain Internet connectivity. The combination of
smartphone and vehicle surface pressure observations may well contribute to a substantial
increase in our ability to describe and forecast the atmosphere at high resolution, with substantial
economic benefits and the potential to save lives and property.
Acknowledgments

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References


Figure Captions

Figure 1: Surface pressure locations for a typical contemporary period (0000 UTC November 10, 2012 through 2100 UTC December 10, 2012) from roughly 70 networks over the Pacific Northwest. Figure from Madaus et al. (2013).

Figure 2: The Samsung Galaxy S4 is one of several Android phones with high-quality pressure sensors.

Figure 3: Verizon cell phone coverage map on 10/04/2013. Darker red areas indicate enhanced digital coverage. White areas are without coverage.

Figure 4: Smartphone pressure observations for the hour ending 2000 UTC November 15, 2013. A total of 21,283 observation locations were available at this time. Data are provided by two commercial firms: Cumulonimbus and OpenSignal.

Figure 5: Smartphone pressure observations (PNET) and pressure measurement sites from ASOS observation locations (METAR) at 0000 UTC 30 June 2013.

Figure 6: Three-hour precipitation from the Pendleton (PDT) radar, as well as ensemble means from the University of Washington real-time ensemble-Kalman filter system (RTENKF) and the same system using pressures from smartphones, for a three-hour period ending at 0000 UTC 30 June 2013.

Figure 7: The number of ensemble members with a local maxima in 3-hour precipitation of at least 20mm at each gridpoint ending at 0000 UTC 30 June 2013 for the operational University of Washington EnKF data assimilation system (RTENKF) and a similar system that also assimilates
smartphone observations (PNET). An exclusion radius of 40km was used to isolate independent maxima. The 10mm 3-hour precipitation derived from the PDT radar is also outlined. More ensemble members indicated a maximum of precipitation near an observed convective location when smartphone pressures were assimilated.
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