[DL12]- Executive Summary Report

Weather Monitoring based on Collaborative Crowdsourcing

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Table of content

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References

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Acronyms

AROME	French meteorological model
ARPEGE	Global meteorological model
CPF	Central Processing Facility
DF	Dual Frequency
GAL	Galileo
GLO	GLONASS
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
METAR	METeorological Airport Report
NLS	National Land Survey
NWM	Numerical Weather Model
NWP	Numerical Weather Prediction
PPP	Precise Point Positioning
PWV	Precipitable Water Vapour
RCV	Receiver
SF	Single Frequency
STD	Slant Tropospheric Delay
SYNOP	Meteorological observations at Earth’s surface
WMCC	Weather Monitoring based on Collaborative Crowdsourcing
ZTD	Zenith Tropospheric Delay
ZWD	Zenith Wet delay

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1. Introduction

The main goal of this project is to assess the feasibility of estimating tropospheric delays using GNSS data from a network of smartphone GNSS receivers in order to improve the precision of NWP models.

This document is an executive summary report that concisely summarizes the findings of the project.

2. Executive summary

2.1 CONTEXT

Troposphere is the lowest part of the Earth's atmosphere and it is where weather happens. The troposphere generates on GNSS signals a code and phase delay. This delay can be separated in two components:

- Hydrostatic delay can be accurately predicted (a few mm accuracy) using an analytical model [4].
- Wet delay is caused by the water vapour, and is hard to model. Due to its dynamic nature, its distribution varies spatially and temporarily. The GNSS delay from water vapour represents around 10% of the total tropospheric delay. The water vapour distribution extends to the height of about 10 km, but most of its mass mainly resides below 1-3 km.

In order to improve weather forecast, wet tropospheric delays are of particular interest for numerical weather models (NWMs) since they contain water vapor content information. For this reason, some NWMs currently assimilate GNSS-based wet tropospheric delays estimated by networks of high-grade (geodetic) GNSS receivers [3][2]. The shortcoming of this technique is the limited amount of these base stations.

GNSS smartphone receivers, however, could provide additional data that would – in the best scenario – significantly improve the coverage and density of the GNSS-based tropospheric delay estimation, while decreasing the infrastructure and maintenance cost of high-grade GNSS receiver networks. The number of smartphones equipped with chipset GNSS receivers is currently experiencing strong growth. The most recent chipsets are multi-constellation receivers (Samsung S8 and Huawei P10), and the first multi-frequency smartphone is on the market (Xiaomi Mi8) and is equipped with Broadcom BCM47755 chip.

This project aims to assess the feasibility of estimating wet tropospheric delays for weather monitoring applications using GNSS and meteorological observables from a high number of GNSS smartphone receivers. One of the main findings of this project is the development of a crowdsourcing-based technique that fuses GNSS and meteorological data from a network of smartphones to evaluate the 2D or 3D content of the troposphere and to estimate the zenith tropospheric delays. Overall, the zenith total tropospheric delay (ZTD) is accurately estimated through this collaborative management.

2.2 PROJECT WORK STEPS

In order to reach the project objective, the **work has been organized** as follows:

- Design and definition of the Weather Monitoring based on Collaborative Crowdsourcing (WMCC) system architecture. This includes the identification of the components of the system (HW and SW), the definition of the minimal requirements related to each system component, the definition of the data interfaces between each components and the way to manage data within the system.
- Design, definition, implementation and validation of a simulation test-bed that emulates the WMCC system.
- WMCC system performance analyses through an experimental campaign based on the simulation test-bed.
- Analyses of the system performances, summary of lessons learnt, conclusions and recommendations.

2.3 MAIN PROJECT FINDINGS

The **main findings** related to this project are presented hereafter.

Firstly, a WMCC system architecture has been proposed and recommended. This architecture consists of:

- A Smartphone network. Each smartphone of the network shall be equipped by:
    1. A GNSS receiver that estimates the GNSS carrier phase measurements. If this receiver is SF, it shall receive at least 3 constellations. If this receiver is DF, it shall receive at least GPS constellation. The GNSS receiver shall be able to track GNSS carrier phase measurements with a data rate of 1 second.
    2. A barometer that measures the pressure at the smartphone location. The performance level of this barometer shall be at least the performance of the most recent smartphone barometers such as Bosh BME280.

- Data link between the smartphones and a Central Processing Facility (CPF). This data link shall be able to transmit GNSS and pressure data from each smartphone to the CPF.

- CPF. It shall be equipped with:

1. A connexion to precise ionospheric products and ultra-rapid precise orbit and clock products to mitigate the ionospheric delays and the satellite clock and ephemeris errors affecting the GNSS carrier phase measurements.
2. A processing unit able to process the GNSS carrier phase measurements, receiver height estimates, smartphone temperature and pressure estimates from the receivers.
3. An internet connexion to:
   - download data (NWM data) necessary to remove bias from tropospheric delays estimated by the processing unit.
   - download data (METAR/SYNOP or NWM data) necessary to estimate receiver height and temperature of each smartphone. Indeed, the accuracy level of smartphone thermometer is not in line with the weather monitoring application, it is thus preferred to download and interpolate external data to estimate the temperature at the smartphone location.

- Data link between the CPF and the NWM. This data link shall be able to transmit the ZTD estimated by the CPF to the NWM.

Different trade-offs have been proposed to choose the number of CPF in the system, and to choose which processing are performed by the smartphone, and which processing are performed by the CPF. It has been concluded that:

- A centralized architecture is chosen, meaning that a single CPF will process the data from all the receivers of the network,
- The semi-distributed processing approach is chosen, meaning that part of the processing is performed at smartphone level (for example pressure estimation at receiver position), and part of the processing is performed by the CPF (tropospheric delay estimation).

The following figure depicts each system component.

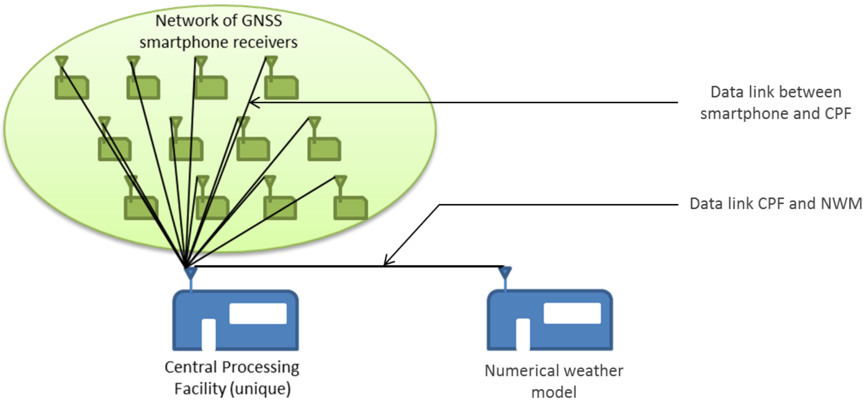

Figure 1: WMCC system architecture

Secondly, a simulation test-bed that emulates the WMCC system has been designed, implemented and validated. The simulation test-bed architecture is presented in the next figure.

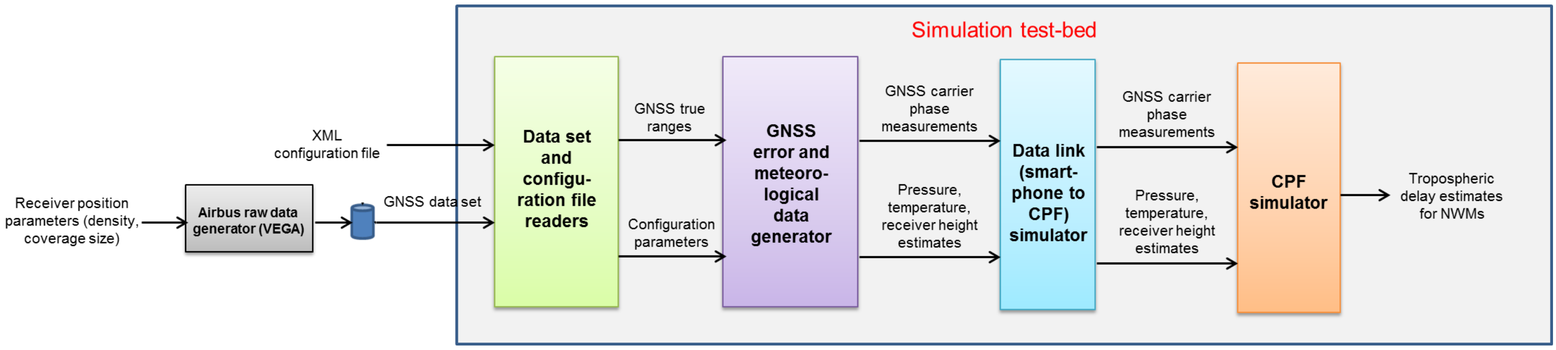

Figure 2: Simulation test-bed architecture

Using receiver position parameters, VEGA computes GNSS true ranges between the GPS, Galileo and GLONASS satellites and the GNSS receivers of the network. The positions of the GNSS receivers are randomly and uniformly distributed over circular areas. GNSS receivers are located at the surface of the Earth. Next the simulation test-bed computes GNSS measurement errors and estimates pressure, temperature and receiver height at the smartphone positions. GNSS and meteorological data are then transferred to the CPF via the smartphone to CPF data link. These data are then processed by the CPF, which outputs tropospheric delays estimates at the NWM format. Note that, in the previous figure, it has been assumed that the receiver height and temperature estimation is performed by each smartphone. However, it is preferred to perform these estimations at the CPF level in order to reduce the processing tasks at smartphone level. In this case, the temperature and height estimations are not transferred through the smartphone to CPF network link.

In order to assess the WMCC system performances under realistic conditions, it is essential to generate on GNSS measurements tropospheric delays and receiver-related errors that are representative of reality. This generation is performed by the GNSS error and meteorological data generator block. In order to develop a simulator test-bed that is representative of the reality, it has been chosen to use real data to generate tropospheric delays and receiver-related errors:

- Tropospheric delays are generated using AROME/ARPEGE data base. ARPEGE (global model) and AROME (French model) are high resolution NWMs developed by Météo France. ARPEGE has a horizontal spatial resolution of roughly 10 km, while AROME propose meteorological data with a spatial resolution of 1-2 km. Using these data bases enables representing small scale (km level) troposphere events, such as local storms or convective cells.
- Receiver-related errors are generated using error models that are specific to smartphone receivers and that have been developed in the frame of the project. More precisely, these error models have been derived by processing smartphone (Samsung S8 and Huawei P10) GNSS data collected by NLS in winter 2018 in the frame of this project [5].

The development of a simulation test-bed that emulates tropospheric delays and receiver-related errors in a representative way is one of the main outputs of this project.

Another important outcome of the project is the development of an innovative crowdsourcing-based technique that fuses GNSS and meteorological data from a network of smartphones to evaluate the tropospheric water vapour distribution and to estimate the tropospheric delays. This algorithm is implemented in the CPF. The tropospheric water vapour distribution is computed using the tomography technique. Tomography means estimating the spatio-temporal tropospheric water vapour distribution. [1] is the first to employ GPS slant wet delays from multiple receivers to obtain a 4x4x40 voxel grid (xyz) on a region of 400 km^2 and 15 km in height to produce 4D wet refractivity fields. As an illustration, the next figure depicts a single layer voxel grid that can be used to retrieve the tropospheric water vapor distribution through the tomographic technique.

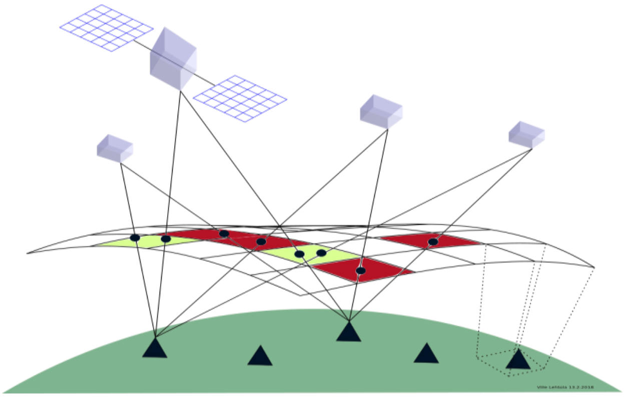

Figure 3: The proposed tomographic model. The wet delay / PWV distribution is discretized in a grid. Multiple layers may be used to increase vertical resolution. Black triangles are GNSS receivers.

From this tropospheric water vapour distribution estimation, we can derive the zenith wet delay at each cell centre.

One major difference with the previous tropospheric tomography and this study is that we have to estimate the receiver positions simultaneously while we are constructing the wet delay distribution estimate. The novelty of this approach is neither in the receiver position estimation, which itself is well known, nor in the tomography per se, as several tomography studies exists. Rather, the novelty lies in how these two steps are combined with a recursive approach. The following sketch illustrates the combination between the tomography and the receiver position estimation steps.

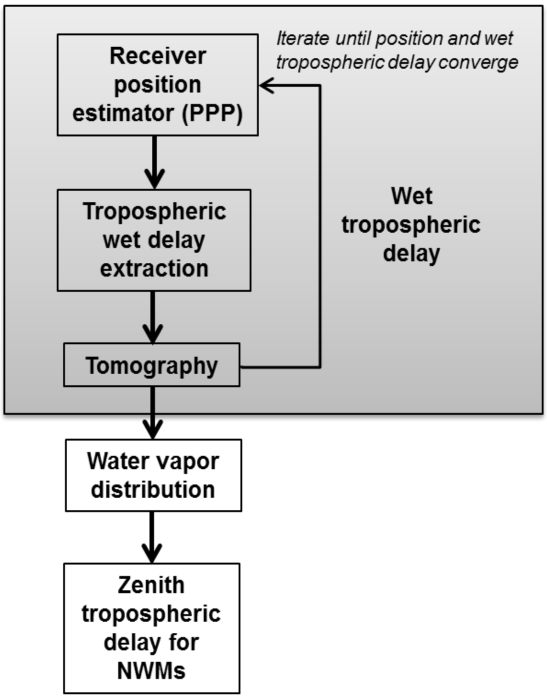

Figure 4: Combination between the tomography and the receiver position estimation steps

Thirdly, the tropospheric delay estimation technique performances have been analyzed using the developed simulation test-bed and considering different nominal and degraded conditions:

- In the nominal experimentations, the impact of the GNSS constellations (GPS, Galileo, and/or GLONASS), the GNSS frequencies (single or dual frequency), and the smartphone density have been analyzed on the tropospheric delay estimation.
- In the degraded condition experimentations, the impact of the GNSS receiver grade, the GNSS multipath environment (open-sky or urban conditions), the GNSS data gaps (due to data link loss or receiver duty cycles), and the atmospheric conditions (such as degraded ionosphere conditions) have been analyzed on the tropospheric delay estimation.

In this experimental phase, up to 1000 receivers have been simulated in local (25km diameter) or regional (250km diameter) areas.

Experimental analyses have shown that the following parameters have a significant impact on the ZTD estimation error:

- The receiver density. Dense receiver networks (density of 1.0 receivers/km² or higher) enable limiting the tropospheric delay estimation error to roughly 10cm (before tropospheric delay bias estimation and removal), while networks characterized by a lower network density show tropospheric delay estimation errors that can reach several decimeters.

- The GNSS constellation mode. The use of the triple constellation significantly improves the tropospheric delay estimation accuracy compared to the use of double or single constellation.

- The GNSS frequency mode. The single frequency (SF) mode can only be used in triple constellation (GPS+GLO+GAL) for the weather application when receiver density is 1.0 receiver/km² or lower.
  The best tropospheric delay estimation performances are obtained for the DF mode in tri constellations. In this case, the tropospheric delay accuracy level is roughly 1cm (before tropospheric delay bias estimation and removal).

- The receiver grade, the receiver multipath environment, and the ionospheric conditions. Low-grade receivers, urban environments, degraded ionospheric conditions may lead to degrade the quality of the ZWD estimation. As an illustration, the number of ZTD assimilated in NWMs is decreased by roughly 20% when using smartphone GNSS receivers instead of medium-grade GNSS receivers.

- The GNSS data gaps. The link losses between the smartphones and the CPF (network failures) or receiver duty cycles have a significant impact on the tropospheric delay estimation if they affect a majority (more than 50%) of the GNSS receivers.

In the following table, different constellation and frequency configurations are presented with a colour code indicating the suitability of the configuration regarding the weather monitoring application.

Configuration	GPS SF	GPS DF	GPS+GAL+GLO SF	GPS+GAL+GLO DF
Recommended	🟥	🟨	🟨	🟩
Remark	ZTD estimation error > 10 cm (*)	Performance slightly better than multi-constellation in SF	ZTD estimation error > 10 cm (*)	In local coverage, ~1 cm (*) ZWD error estimation can be achieved

Table 1 - Project recommendation on the usage of the different configurations for receivers density of 1.02 receiver/km² or less. Colour code: green for the recommended configurations, yellow for configurations that are not recommended but can be used and red for configurations that are not recommended to be used for this application.

(*) : before tropospheric delay bias estimation and removal

In the following table, different perturbation configurations are presented with a colour code indicating the suitability of the configuration regarding the weather monitoring application.

Configuration	Low-grade receiver	Semi-urban multipath environment	High residual ionospheric errors (for SF only)	Network failures on every RCV	Duty cycles on 50% RCV
Recommended	🟨	🟨	🟨	🟥	🟨

Table 2 - Project recommendation on the impact of internal and external perturbations on the system performances for receivers density of 1.02 receiver/km² or less. Colour code: green for the recommended configurations, yellow for configurations that are not recommended but can be used and red for configurations that are not recommended to be used for this application.

3.4 WAY FORWARD

Finally, way forwards related to the project have been proposed. Particularly, future tasks to prepare the operation and exploitation of the WMCC system have been recommended and are as follows:

- Adapt the tropospheric delay estimator to mobile receivers.
- Perform real data analyses to validate the system performances.
- Perform an analysis to estimate if the receiver density in Europe is sufficient to operate and exploit a WMCC system.
- Perform a trade-off and choose the data link between the smartphones and the CPF. Among the possible data links, it can be envisaged to develop a crowdsourcing application which would allow smartphone users to upload GNSS and meteorological data. Then the CPF would use the data base from this application to estimate the ZTD.

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