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Comparison of tropospheric parameters from Meteodrone measurements with GNSS estimates from ground-based stations

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Abstract

This study presents a comparison of tropospheric parameters, namely zenith tropospheric delay and total refractivity calculated using meteorological measurements from a Meteodrone and Global Navigation Satellite Systems (GNSS) stations. A Meteodrone is a unique Unmanned Aerial Vehicle (UAV) originally designed for automatic measurements of meteorological parameters in vertical profiles (up to 3 km above ground) for the assimilation into numerical weather prediction models. One profile measured with both ascending and descending drone takes approximately 20 minutes, and there are multiple flights possible during one night. The measurements for this campaign have been conducted in March 2019, in Marbach, Switzerland. We have collected pressure, temperature and humidity profiles from nine flights. From the measured meteorological parameters, we have calculated the refractivity and zenith tropospheric delays (*ZTDs*). The parameters are compared with models calculated from 32 neighboring permanent GNSS stations interpolated using the in-house developed least-squares collocation software COMEDIE (COLlocation of MEteorological Data for Interpretation and Estimation of tropospheric path delays). The comparisons between the meteo-drones and the GNSS-derived models show a good agreement with an average absolute bias of 2.4 mm with 1.5 mm standard deviation for *ZTD* and 2.7 ppm with 1.7 ppm standard deviation for the comparison of the refractivity. The bias is a result of local changes of meteorological conditions captured by the drone, but not by the interpolation model.

Keywords: Meteodrones, UAV, GNSS, troposphere, zenith total delay, refractivity

1. Introduction

Water vapor is the most variable parameter of the troposphere and the most abundant greenhouse gas (Bevis et al., 1992). It is also the most critical parameter to observe and accounts for the majority of the errors in the troposphere modeling. A traditional technique for observing the water vapor distribution

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are radiosoundings. The radiosonde is a device measuring meteorological parameters, i.e. air pressure, temperature and humidity, carried by a free-flying balloon up to a height of about 30 kilometers above sea level (asl). Every 30 seconds, the measured values are transmitted to the aerological station using a shortwave transmitter. The measurements are carried out usually twice a day. The spatial resolution of the station's distribution is sparse, usually around 250 kilometers or more in Europe (Guerova et al., 2016).

Another way of observing the water vapor distribution is by using the Global Navigation Satellite Systems (GNSS). This method is called GNSS meteorology, originally GPS meteorology (Bevis et al., 1992) and has been gaining more and more interest over the years. Currently, there are four GNSS constellations with global coverage in operation: US American GPS-NAVSTAR, Russian GLONASS, European Galileo and Chinese Beidou. When a GNSS signal passes through the neutral atmosphere, it is delayed by the refraction with its variations caused mainly by the water vapor. The tropospheric delay used to be considered only as a source of error that needed to be removed. Nowadays, these delays are also a source of interest; e.g. GNSS products are assimilated into nowcasting (Smith et al., 2007; Seco et al., 2009; Manning et al., 2012; Benjamin et al., 2016) or numerical weather prediction (NWP) models (Vedel and Huang, 2004; Poli et al., 2007; Shoji et al., 2009; Zus et al., 2011; Bennitt and Jupp, 2012; Lindskog et al., 2017; Rohm et al., 2019). Moreover, long time series of GNSS observations have become an important source of information for climate studies (Vey et al., 2009; Ning et al., 2013; Alshawaf et al., 2017; Parracho et al., 2018; Klos et al., 2018). On the other hand, the meteorological data can support the GNSS processing, for example in initialization of precise point positioning (PPP) processing algorithms, where the high accuracy troposphere model can shorten the convergence time (Hobiger et al., 2008; Hadaś et al., 2013; Wilgan et al., 2017b; Lu et al., 2017; Wang and Liu, 2019).

A crucial aspect of all the above-mentioned applications is the assessment of the GNSS data quality. The GNSS-based models are often tested against reference data, which can be NWP models (Vedel et al., 2001; Bock et al., 2005; Teke et al., 2011; Wilgan et al., 2017a; Kacmarík et al., 2017), radiometers (Bevis et al., 1992; Duan et al., 1996; Li et al., 2014; Wang and Liu, 2019), or blind models (Wielgosz et al., 2012; Möller et al., 2014) such as the Global Pressure and Temperature (GPT) (Boehm et al., 2007) or the UNB3 (Leandro et al., 2006) models. In the vertical profiles of the atmosphere, the radiosonde measurements are still the state-of-the-art method of a validation (Karabatić et al., 2011; Hurter and Maier, 2013; Rohm et al., 2014; Van Malderen et al., 2014; Douša et al., 2016; Wilgan and Geiger, 2019). However, the soundings are not error-free (Soden and Lanzante, 1996; Wang and Zhang, 2008; Löhnert and Maier, 2012). Apart from the limited temporal and spatial resolution, the radiosonde does not ascend perfectly vertically, as it is carried away by the wind. Moreover, the measuring devices usually cannot be reused after flights, thus, their use is also resource-intensive.

We have conducted a proof of concept campaign of determining the refractivity and consequently the delays at different altitudes using a Unmanned Aerial Vehicle (UAV) called Meteodrone from the Swiss

company Meteomatics. The Meteodrones were designed for automatic measurements of meteorological parameters in vertical profile for the assimilation into NWP models. For this campaign, the measurements are carried out in Marbach, Switzerland, the test launch site of Meteomatics, during one night with multiple ascends and descends of the drone. Daily flights in many regions are still restricted due to air traffic.

The aim of this work is to compare the measurements from the Meteodrone with the tropospheric parameters from GNSS. For this purpose, the surrounding GNSS permanent stations and three temporarily set-up geodetic GNSS receivers were used to estimate the zenith tropospheric delay (*ZTD*) and the total refractivity. The GNSS estimates are interpolated to the locations of the drone measurements using the in-house developed software COMEDIE (COLlocation of MEteorological Data for Interpretation and Estimation of tropospheric path delays) (Eckert et al., 1992a,b). The *ZTD*s and total refractivity from both data sources are compared for all the height levels of the Meteodrones flights.

The Meteodrone is a unique device, as it measures the meteorological parameters, wind and position of a drone. There are a few other studies about meteorological parameters from a drone, but they are mostly covering aspects related only to the wind (Van den Kroonenberg et al., 2008; Niedzielski et al., 2017). The drones were initially equipped with a single frequency GPS receiver for measuring the location of the drone. We have additionally installed a dual-frequency u-blox receiver to calculate the GNSS *ZTD*s from the moving drone. The decorrelation of the height and the troposphere for this data set is, however, a non-trivial task and needs further studies.

This chapter is followed by Section 2, introducing the experiment and the data sources. Section 3 describes the methods of converting the meteorological observations into tropospheric parameters and the method of the GNSS data interpolation. Section 4 presents the comparison between the GNSS and Meteodrone data, Section 5 discusses the reasons of the differences between the techniques and Section 6 summarizes the study.

2. The experiment

In this section, we describe the characteristics of the Meteodrone and the set up for the measurement campaign.

2.1. The Meteodrone

The Meteodrone from Meteomatics AG (www.meteomatics.com) is equipped with sensors that measure temperature, wind speed, wind direction, dew point temperature, relative humidity and air pressure with a sampling rate of 250 ms. Figure 1 shows the picture of the Meteodrone at the launch site. The drone size is 70 cm $\times$ 70 cm and its weight is about 1.5 kg. The maximum climb rate is 10 m/s, and the theoretical maximum altitude is 3000 m above the ground. The uncertainty of the meteorological sensors

Figure 1: The Meteodrone at the launch site. The red cover protects the emergency parachute.

for temperature, air pressure and relative humidity are given in Table 1. The drone has a Beyond Visual Line-Of-Sight (BVLOS) permit issued by the Federal Office of Civil Aviation (FOCA), which means that it is able to fly within clouds and in a fog. The Meteodrone has a water resistant certificate IP64, thus, it is also capable of flying in the rain. The main limitation is the severe wind: the drone cannot be operated with the wind exceeding 50 km/h.

Table 1: The uncertainty of the meteorological sensors on board the Meteomatics Meteodrone (Hammerschmidt 2019, private communication)

parameter	standard deviation
temperature	± 0.1 K
air pressure	± 1.5 hPa
relative humidity	$\pm 1.8\%$ (between 0 - 90%)

2.2. The experimental set-up

The flights were carried out in the night of March 28 - 29, 2019 at the test launch site of Meteomatics; close to the municipality of Marbach, canton St. Gallen, Switzerland. The site is located at around 413 m asl. Prior to the launch, two geodetic Leica GR10 GNSS receivers were installed a few kilometers away from the launch site at different altitudes, one in Chornberg at about 740 m asl and one in the St. Anton Pass

Figure 2: The vicinity of the launch area with the installed GNSS receivers.

at about 1090 m asl. Moreover, a Septentrio PolRx5 GNSS receiver was installed at the drone launch site. Figure 2 shows the location of the temporary stations.

2.3. The flights

At first, a test flight was completed to check if the wind at different altitudes allows for carrying out the experiment. During the test, the drone has only reached the altitude of about 2300 m asl due to a strong wind (more than 10 m/s) encountered at that height. Afterwards, eight flights were performed, with only three flights reaching and even slightly exceeding the planned height of 3000 m above the ground, which corresponds to around 3413 m asl. Table 2 shows a list of all the flights. The climb rate of the drone at the beginning of the flights was approx. 5.7 m/s. To assure the safety of the flight despite the wind, the climb rate was temporarily reduced. The average time of one flight was 15-20 minutes. The meteorological parameters and positions were recorded with a sampling rate of 4 Hz producing from around 3000 observations for the shorter flights to 5000 for the longer flights.

2.4. GNSS reference stations

The measurements from the Meteodrone are compared to the interpolation model derived from GNSS data. Figure 3 shows the location of the 32 GNSS stations used to build the model. The following networks from three countries are utilized:

- Temporary stations set up by ETH (CH) (3 stations)

Table 2: The list of conducted flights during the night of March 28-29, 2019.

Flight No.	Time UTC	Maximum height	Limitation
1	21.51 - 22.05	2353 m asl	wind
2	22.31 - 22.43	2280 m asl	wind
3	22.58 - 23.10	2185 m asl	wind
4	23.22 - 23.35	2144 m asl	wind
5	23.51 - 00.12	3412 m asl	-
6	00.16 - 00.35	3423 m asl	-
7	00.37 - 00.58	3020 m asl	wind
8	01.11 - 01.32	3407 m asl	-
9	01.51 - 02.12	2974 m asl	wind

- Automated GNSS Network for Switzerland (AGNES) provided by the Swiss Federal Office of Topography (swisstopo) (CH) (12 stations)
- REFNET provided by geotopo (CH) (4 stations)
- Leica Geosystems Network (CH) (3 stations)
- Satellite Positioning Service of the German Surveying (SAPOS) provided by SAPOS-BY and SAPOS-BW (DE) (2 stations)
- Austrian Positioning Service (APOS) provided by Federal Office of Metrology and Surveying (BEV) (AU) (3 stations)
- Echtzeit Positionierung Austria (EPOSA) provided by TU-Wien (AU) (4 stations)
- EUREF Permanent GNSS Network provided by TU-Wien (AU) (1 station)

Figure 4 shows the height distribution of the stations. They are located at a variety of heights, from 411 m asl to 2208 m asl. The majority of the stations (21) is located below 1000 m asl. A GPS double difference phase solution with fixed ambiguities was computed for the selected GNSS stations using the Bernese GNSS software version 5.2 (Dach et al., 2015). The ZTDs were modeled as piece-wise linear functions with a sampling of 1 hour. The elevation cut-off angle was set to 3° and the mapping function was GMF (Global Mapping Function).

3. Methodology

We compare the refractivity and ZTD obtained from meteorological measurements from the drone with the interpolated values from the surrounding GNSS stations. In this section, we present the methods of

Figure 3: The location of GNSS stations from different networks used to build the interpolation model. The green polygon shows the 14 stations closest to the Meteodrones launch site.

Figure 4: The height distribution of the 32 GNSS stations used in the interpolation model.

calculating the tropospheric parameters for all the flight levels.

3.1. Calculation of tropospheric parameters

The Meteodrones measure temperature T [K], air pressure p [hPa] and relative humidity RH [%]. To calculate the total refractivity N [ppm], the relative humidity must be converted into water vapor partial pressure e [hPa]. Firstly, we calculate the water vapor partial pressure of the saturated air e_{sat} using the Clausius-Clapeyron formula (Haltiner and Martin, 1957):

$$e_{sat} = e_{sat,0} \cdot \exp \left[\frac{-L}{R_v} \cdot \left(\frac{1}{T} - \frac{1}{T_0} \right) \right], \quad (1)$$

where: $T_0 = 273.13$ K and $e_{sat,0} = 6.11$ hPa are the reference values at 0° C; $R_v = 461.525$ J·kg⁻¹·K⁻¹ is the specific gas constant of water vapor and L is either the latent heat of vaporization ($L_1 = 2.5 \cdot 10^6$ J·kg⁻¹ for $T > 273.15$ K) or sublimation ($L_2 = 2.834 \cdot 10^6$ J·kg⁻¹ for $T < 273.15$ K). Then, we calculate the water vapor partial pressure e [hPa] from relative humidity RH [%] as:

$$e = \frac{RH \cdot e_{sat}}{100\%}. \quad (2)$$

From the temperature, air pressure and water vapor partial pressure, we calculate the total refractivity N [ppm] for each drone measurement (Essen and Froome, 1951):

$$N = k_1 \cdot \frac{p_d}{T} \cdot Z_d^{-1} + k_2 \cdot \frac{e}{T} \cdot Z_w^{-1} + k_3 \cdot \frac{e}{T^2} \cdot Z_w^{-1} \quad (3)$$

where $p_d = p - e$ is the dry air pressure; Z_d^{-1} and Z_w^{-1} are the dry and wet compressibility factors and are usually set to one; $k_1 = 77.689 \frac{\text{K}}{\text{hPa}}$, $k_2 = 71.295 \frac{\text{K}}{\text{hPa}}$ and $k_3 = 375463 \frac{\text{K}^2}{\text{hPa}}$ are the refractivity constants, in this study taken from Rüeger (2002) as ‘best average’. From the refractivity at each level, we calculate the ZTD as:

$$ZTD = 10^{-6} \cdot \int_{z_d}^{\infty} N(h) dz. \quad (4)$$

where z_d is the orthometric height of the drone at the observation. Eq. 4 can be written in a discrete form as:

$$ZTD \approx 10^{-6} \cdot \sum_{i=1}^{top-1} \left(\frac{N_i + N_{i+1}}{2} \right) \cdot \Delta z_i, \quad (5)$$

where Δz_i is the height difference between i -th and $(i+1)$ -th level and top is the uppermost level of the drone measurement. Thus, the delay is not calculated for the entire troposphere, but from the chosen level (starting at the ground) to the top level.

3.2. Interpolation of GNSS data

The GNSS zenith path delays are interpolated at the location of drone measurements using the least-squares collocation software COMEDIE developed at ETH Zurich (Eckert et al., 1992a,b; Troller, 2004; Hurter and Maier, 2013; Wilgan et al., 2017a). The collocation technique divides each measurement into a deterministic part (trend), a correlated stochastic (signal), and uncorrelated stochastic part (noise). Using the input data, the parameters of the trend are estimated in the least-square sense. For the ZTD , we use the following formula describing the deterministic model:

$$ZTD(x, y, z, t) = [ZTD_0 + a(x - x_0) + b(y - y_0) + c(t - t_0)] \cdot e^{-\frac{z-z_0}{H_0}}, \quad (6)$$

where x, y, z, t are the Swiss projected coordinates LV03¹, orthometric height and time of the investigated point; $x_0, y_0, z_0 = 0, t_0$ are the projected coordinates, height and time of the reference point. In case it is not defined, the reference point is calculated in the collocation procedure as an average from all input points for each time batch. The ZTD_0 is the ZTD at the reference position and time t_0 , H_0 is the scale height and a, b, c are the gradient parameters in x, y and time, respectively. The parameters ZTD_0, H_0, a, b, c are the unknowns in the collocation procedure and are estimated for each time batch.

The signal is assumed to be normally distributed with mean zero and the covariance matrix C_{ss} depending on the distances between the measurements. The covariance function for ZTD is chosen to be:

$$C_{ss}(i, j) = \frac{\sigma_{signal}^2}{1 + \left[\left(\frac{x_i - x_j}{\Delta x_0} \right)^2 + \left(\frac{y_i - y_j}{\Delta y_0} \right)^2 + \left(\frac{z_i - z_j}{\Delta z_0} \right)^2 + \left(\frac{t_i - t_j}{\Delta t_0} \right)^2 \right] \cdot e^{-\frac{z_i + z_j}{2z_0}}}, \quad (7)$$

where σ_{signal}^2 is the a-priori variance of the signal, x_i, y_i, z_i, t_i are the projected Swiss coordinates, orthometric height, and time of observation i ; x_j, y_j, z_j, t_j are the coordinates, height and time of observation j ; $z_0 = 4$ km is the parameter modifying the correlation lengths as a function of height; $\Delta x_0 = 50$ km, $\Delta y_0 = 50$ km, $\Delta z_0 = 1$ km, $\Delta t_0 = 1.7$ h are the empirically determined correlation lengths of space and time.

The GNSS-based ZTD s are calculated for each level of the Meteodrone flights. The delays from the drone are only partial, calculated until the uppermost level of the drone flight. Thus, we also calculate only the partial delays from the GNSS data. For that we subtract the GNSS ZTD s interpolated at the top level from the delays for the lower levels.

Since the ZTD is an integral of total refractivity (Eq. 4), the deterministic model for N can be obtained by applying a differential operator $D = \frac{\partial}{\partial z}$ to Eq. 6, yielding the deterministic model of refractivity:

$$N(x, y, z, t) = \frac{1}{H_0} [ZTD_0 + a(x - x_0) + b(y - y_0) + c(t - t_0)] \cdot e^{-\frac{z-z_0}{H_0}}, \quad (8)$$

¹<https://www.swisstopo.admin.ch/en/knowledge-facts/surveying-geodesy/reference-frames/local/lv03.html>

To derive the covariance functions between N and ZTD as well as between two refractivity measurements, the operator D is applied to the covariance function of ZTD (Eq. 7). For more detail, please refer to Wilgan et al. (2017a) or Hurter and Maier (2013).

4. Results

In this section, we present the comparison of the retrieval of tropospheric parameters by the drone measurements and by the interpolation model from GNSS. The emphasis is on the ZTD and total refractivity retrievals. At first, we show the meteorological parameters measured by the drone.

4.1. Meteorological measurements from the drone

The Meteodrone measures profiles of the meteorological parameters in both ascending and descending mode. Figure 5 shows the unprocessed measurements of temperature, pressure and relative humidity, respectively, linearly interpolated in between flights for better visualization. The dashed red lines represent the nine drone flights.

Figure 5 shows a shift in the temperature measurements for the same flight and height between the ascending and descending drone. At the same height, the ascending temperature is higher by around 0.5-1 K than the measured temperature during the descend. This can be a result of a down-cooling of the drone in the higher altitudes. Moreover, a thin layer of air directly above the ground is a few degrees colder than the layer above. Furthermore, from the 5th flight onward, a layer of warmer air has formed at about 2250 m, while directly below and above the temperature was lower. For air pressure, there are small differences between the ascending and descending values, but overall, a very homogeneous, stratified pressure distribution is observed. For relative humidity, a layer with higher humidity is visible close to the ground. In the course of the experiment, the humidity in the higher air layers steadily decreases. Although, below 2000 m, individual small cells are recognizable, which contain humidity of over 60%. Since the humidity values fluctuate a lot, a differences between the ascend and descend are not so clearly distinguishable as in the case of temperature. Although, close to the ground, the humidity values from the descending drone are usually higher than for the ascending flight. A similar situation is also visible above 2000 m asl, but with much smaller humidity discrepancies.

Meteomatics provides also the processed data, where all the observations for each flight are reduced to one time (the median time of the flight). The hysteresis between the ascending and descending flight is eliminated. Figures 6 shows the temperature, air pressure and relative humidity, respectively from the processed observations.

In the processed observations, shown in Figure 6, the main features of the weather conditions for the flights are much better delineated. During the night, the temperature is cooling down close to the ground

Figure 5: The raw measurements of temperature (top), air pressure (middle) and relative humidity (bottom) by the drone interpolated between the flights. Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

Figure 6: The processed measurements of temperature (top), air pressure (middle) and relative humidity (bottom) by the drone interpolated between the flights. Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

Figure 7: The ZTD calculated from the raw meteorological measurements by the drone. Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

due to the mostly uncovered sky. However, there is a rise of temperature with simultaneous decrease of humidity at around 2000 m asl. This is due to an inflow of foehn-type of air from southern direction. This wind is also the cause of the shear zone at around 2000 m which has clearly sunk by about 200 m during the night (Figure 6, bottom). The air pressure distribution remains very stratified, depending only on the height.

4.2. Comparison of tropospheric parameters

We calculate the ZTD s from the raw meteorological drone measurements according to Eq. 5. Figure 7 shows the values of ZTD . Please note that the maximum values are at a level of 700 mm, which is due to the fact that we calculate only the partial delays from the ground to the highest altitude of the drone.

Figure 8 shows the differences between ZTD_M from the drone and ZTD_{GNSS} interpolated from the path delays determined at neighboring GNSS stations. To make the ZTD_{GNSS} comparable with ZTD_M , we also calculated partial ZTD_{GNSS} described in Section 3.2.

As shown in Figure 8, the values of ZTD_{GNSS} are in general smaller than the ZTD_M from the drone, especially closer to the surface. Only, during the 5th flight, at a height of about 2000 m, there is an instance when ZTD_M is smaller. During the last two flights, significant differences close to the ground occur. The maximum difference is 14.4 mm and the minimum is -3.3 mm. On average, the absolute differences are around 2.8 mm. Furthermore, we calculated the differences between the processed drone observations and the GNSS interpolation model. Figure 9 shows these differences.

Figure 9 shows similar results to Figure 8: during the 5th flight, at a height of approximately 2000 m, there is an instance, where the ZTD_{GNSS} is larger than the ZTD_M . Moreover, from a time of 200 minutes

Figure 8: The differences between ZTD_M from raw measurements and ZTD_{GNSS} . Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

Figure 9: The differences between ZTD_M from the processed measurements and ZTD_{GNSS} . Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

Figure 10: The differences between ZTD_M from the processed measurements and ZTD_{GNSS} from 14 stations. Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

the largest differences are observed, although, they are smaller than for the raw measurements. The absolute differences are on average 2.8 mm. The maximum value is 11.7 mm and the minimum is -2.4 mm.

There are 32 GNSS stations used in the interpolation model. We test how the solution changes, if we incorporate less GNSS stations into the model. Figure 10 shows the differences between the ZTD_M and ZTD_{GNSS} calculated only from the 14 stations closest to the drone launch site (maximum distance less than 40 km). The selection of the stations is shown in Figure 3 as a green polygon. The stations located in the closest vicinity of the launch site do not have a diversified height resolution as all of the stations. Out of the 14 stations used, 11 are located below 1000 m asl. The highest stations in this data set are: the AGNES station Sargans SAR2 (located at 1217 m asl), the EUREF station Bregenz PFA2 (1043 m asl) and the temporary station on the St. Anton Pass (1090 m asl).

The model calculated from 14 stations has slightly larger differences closer to the ground compared to the ZTD_M than the model based on 32 stations. The maximum difference for the 14-stations model is 14.1 mm, the minimum is -3.2 mm and the average absolute difference is 3.1 mm. For the higher altitudes, the differences between the ZTD_M and ZTD_{GNSS} from 14 stations are close to 0 or even negative compared to the model from all the stations. Figure 11 shows the differences and standard deviations between ZTD_M and ZTD_{GNSS} from all three methods averaged over time, and Table 3 shows the absolute mean, minimum and maximum values of the differences and the standard deviations averaged over all the heights and time.

All of the methods behave very similarly: they all exhibit bias, especially due to the differences in the lower levels, close to the ground. All of the methods have also very small standard deviations, below 2 mm. The lowest standard deviation, of only 1.2 mm, results from the comparisons of ZTD_M with ZTD_{GNSS} from

Figure 11: The differences and standard deviations between ZTD_M and ZTD_{GNSS} from all three methods averaged over time (March 28 - 29, 2019).

Table 3: The mean absolute bias, the minimum and maximum value of the differences and standard deviations between ZTD_M and ZTD_{GNSS} from all three methods averaged over all the heights and time (March 28 - 29, 2019).

method	absolute bias	min. difference	max. difference	standard deviation
	[mm]	[mm]	[mm]	[mm]
raw, 32 stations	2.8	-3.3	14.4	1.7
processed, 32 stations	2.4	-2.4	11.7	1.5
processed, 14 stations	3.1	-3.2	14.1	1.2

Figure 12: The differences between N_M from the processed measurements and N_{GNSS} . Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

14 stations, and is especially low compared to the other methods at altitudes of 1000 and 2500 m asl. The bias for 14 stations is higher close to the ground and becomes negative above the height of 2000 m asl. This may be due to the less varying height distribution of the surrounding stations. The ZTD_{GNSS} models from 32 stations have very similar statistics for both raw and processed observations. Thus, for the comparisons of total refractivity we use only the model from 32 stations and processed Meteodrone measurements.

We compare the total refractivity values from the drone and GNSS data. The refractivity N_M from the p , T , e measurements on the drone is calculated for all the height levels using Eq. 3. The GNSS refractivity N_{GNSS} is interpolated from the zenith path delays of the surrounding stations using Eq. 8. This equation allows us to connect the refractivity with the ZTD s obtained from GNSS measurements. Figure 12 shows the differences between N_M from the Meteodrone and N_{GNSS} from the interpolation model.

Up to the height of about 2000 m asl, the total refractivity from the drone measurements is usually larger than the value interpolated from GNSS. Only during the 5th flight, above the height of 2250 m, the N_{GNSS} is larger. This is also the place where the ZTD_{GNSS} is larger than ZTD_M . The largest refractivity differences occur for 8th and 9th flight at a height of around 1000 m. This is also visible in the comparisons of ZTD s, but because ZTD is an integrated value, the large differences occur already close to the surface. The average differences from all the flights w.r.t. the height and the associated standard deviations are shown in Figure 13.

In the previous studies (Perler et al., 2011; Hurter and Maier, 2013; Wilgan et al., 2017a; Wilgan and Geiger, 2019) comparing the radiosonde and GNSS data, the differences between the two data sources formed an ‘S-shape’. In Wilgan and Geiger (2019), we compared the GNSS-based interpolation model with

Figure 13: The differences and standard deviations between N_M from the processed data and N_{GNSS} averaged over time (March 28 - 29, 2019).

the radiosonde data in Payerne, Switzerland. The average bias calculated from two summer months of data, up to the height of 13 km asl was 2.6 ppm with 5.1 ppm standard deviation. Considering only the heights up to 3.5 km asl, which corresponds to the top altitude of the drone flight, the average absolute bias was of 5 ppm with 8 ppm standard deviation. For this study, the absolute bias is equal to 2.7 ppm with 1.7 ppm standard deviation. The standard deviation for this study is very small, especially close to the surface and at lower altitudes. Above the height of 2000 m asl, we acquired less data due to the strong wind, thus the standard deviation increases slightly for this region. As shown in Figure 13, the differences also follows the ‘S-shape’ but not to the same extent as in the previous studies. We can conclude, that it is an improvement comparing to the previous study, although there remains a bias. The possible reasons for the bias are discussed in the next section.

5. Discussion

The agreement between the tropospheric parameters from the drone and from the surrounding GNSS stations is overall very good. The main reason is that we built the interpolation model based on many GNSS stations located at various heights with some of the stations located very close to the experiment site. Although, there are instances where the agreement is poorer, especially at the lower altitudes for flights 8th and 9th. In this section, we propose an explanation for the worse agreement.

We consider that the differences between the techniques are a consequence of very local meteorological conditions that are measured by the Meteodrone, but cannot be captured by the interpolation model. We take a look at the patterns of the changes of temperature, relative humidity and also wind speed. The

Figure 14: Wind speed for the processed levels of the drone flight. Red dashed lines indicate the time of the flights. The flights took place during the night of March 28 - 29, 2019.

air pressure is uniformly depending on the height and does not show any local features. Figure 14 shows the wind speed, also measured by the drone. Shown before, Figures 5 and 6 present the temperature and relative humidity. According to Eq. 3, in a very simplified way, we may say that an increase of temperature causes a decrease of the total refractivity, while an increase of water vapor partial pressure (proportional to the relative humidity) causes an increase of the total refractivity.

We discuss the differences of total refractivity, because the differences of ZTD are a direct result of the integration of the refractivity. The most significant differences occur:

- Close to the ground for 1st - 7th flights: for this region there is a decrease in temperature, which is no longer visible for flights 8th - 9th. For the two latter flights, there is also an increase in the relative humidity, but there is no respective change in the differences.
- At altitudes 500 - 1500 m asl for flights 7th - 9th: there is a significant increase of wind speed matching these changes, there is also a slight increase of temperature.
- At altitudes 1500 - 2000 m asl for flights 7th - 9th: there is a relative humidity decrease, although there are no other significant changes in other parameters.
- At altitudes 500 - 1000 m asl for flights 4th - 5th: there is an increase in relative humidity (visible especially in the raw measurements).
- At altitudes 1000 - 1500 m asl for flights 4th - 5th: around these heights, the wind speed starts to increase significantly.

- At altitudes 2000 - 2500 m asl for the 1st flight: the wind speed increased so significantly, that the flight was no longer possible.
- The negative difference for flight 5th at altitude of 2250 m asl: there is a significant temperature increase and then decrease for that flight at this height, which may explain why the difference is so local. There is a very clear line of change in the relative humidity values between 2000 and 2500 m.

Most of the refractivity differences between the drone and GNSS models can be explained by local variations of meteorological parameters. Although, not all of the differences between refractivities are articulated in the differences between *ZTDs*. The largest *ZTD* differences are found for the first and the two last flights for the altitudes up to about 1000 m asl, which may be a result of accumulated differences of refractivity. Although, there are also differences in the refractivity for flights 4th and 5th that do not correspond with large differences of *ZTD* for these flights. This may be due to the fact that for these flights there are positive differences of refractivity in the lower altitudes and negative above 2000 m which may have canceled out in the *ZTD* differences as a result of an integration.

The plan for this study was to also obtain the tropospheric GNSS estimates directly from the drone using the Bernese GNSS software version 5.2. The drone was equipped with a low-cost dual frequency u-blox ZED-F9P GNSS receiver and ANN-MB antenna. A double difference solution should be determined between the u-blox ZED-F9P on the drone and the Septentrio PolaRx5 on the ground. However, the Bernese GNSS software does not yet fully support the estimation of kinematic positions and *ZTDs* for the present application. For this reason, this approach has not been pursued for the time being. A new software has to be developed that can successfully de-correlate the heights and the tropospheric delay, similar to for example the kinematic PPP software G-Nut/Geb developed at Geodetic Observatory Pecny. Although, it has been demonstrated in Václavovic et al. (2017) in a hot-air balloon experiment that even with a specialized software, there are still issues with the de-correlation of the heights and *ZTDs*.

6. Summary

In this study, we compared the tropospheric parameters calculated from the Meteodrone measurements with the values interpolated from GNSS stations surrounding the launch site. The interpolation was performed using the in-house developed least-squares software COMEDIE. Firstly, we compared the tropospheric path delays. The *ZTDs* determined from the Meteodrones measurements are largely in a good agreement with the values interpolated from the GNSS. We compared three methods of calculating the data: 1) using raw Meteodrone measurements vs. the interpolation model from 32 GNSS stations, 2) using processed Meteodrone measurements vs. the interpolation model from 32 GNSS stations and 3) using processed Meteodrone measurements vs. the interpolation model from 14 GNSS stations. All the comparisons

yield similar results, although the lowest absolute bias was obtained for the comparison 2). The results have also shown that the number and height distribution of the stations used to build the interpolation model affect the interpolation. We achieved a better agreement using more stations with more diversified height distribution. The standard deviations from all methods were below 2 mm. Furthermore, we compared the total refractivity from the best previous method. There was a small bias of 2.7 ppm observed between the drone and GNSS models with a standard deviation of 1.7 ppm. Even though, the average statistics were very optimistic, we investigated the reasons of the instances of a worse agreement between techniques. Most of the differences are due to local changes of meteorological conditions, i.e. temperature, relative humidity and wind that are captured by the drone but not by the interpolation model.

This study was a proof of concept experiment, which showed the feasibility of calculating tropospheric path delays from the drone measurements. For the future, a more comprehensive analysis is recommended, with longer time series, flights during daytime and in the summer for more variability of water vapor. Moreover, to obtain the *ZTDs* directly from the low-cost dual-frequency GNSS receiver on-board the drone, a new software must be developed that can successfully de-correlate the heights and the tropospheric delay.

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