Investigation of the dependence between digital height readings and the meteorological parameters by using a stand-alone set up and repeatable short term measurements

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ABSTRACT

The need of high accuracy geodetic measurements, especially in the vertical displacements control networks, is nowadays extended and thus the thorough investigation of all possible error sources is necessary. Despite the technological improvement the accuracy of geodetic measurements is still limited mainly due to the unpredictable propagation of a sighting line. These error sources are concentrated on the variations of the refractive index; witch either bends or retards the electromagnetic wave path and is caused of air density inhomogeneity, which is in terms influenced by fluctuations of the atmospheric parameters.

The present paper aims to the determination of the dependence between digital height readings and the air temperature as well as the atmospheric pressure by performing repeatable short term measurements. Thus, a stand-alone set up of a high accuracy digital level was developed and both indoors and outdoors experiments were carried out for a time period of several days with a time interval of five minutes. At the same time there was an air temperature sensor functioning, which was mounted on the staff, and a meteorological station.

Hence the additional time series were generated and correlation coefficients were computed in order to investigate as much as the linear as well as the monotonic relationships among the measured parameters. Also the repeatability of the digital level's height readings was calculated. The basic term is that the meteorological conditions are stable, which means that heat flux effects are not applied. Thus the influence of the meteorological parameters regarding the level's repeatability was detected while moderate and poor correlations were computed between the acquired data.

I. INTRODUCTION

Spirit leveling is one of the cheapest, oldest and still remains one of the most accurate method in order to compute height differences. Especially today where the demand of high accuracy geodetic measurements is intense for the needs of deformation and monitoring surveying and the assessment of the mechanical response of buildings and technical structures by the determination of vertical displacements.

This fact occurs because of the elimination of most errors, which is based on their reciprocal neutralization regarding a single set up between the level and the staffs, when the geodetic leveling technique is applied. Additionally when a single height reading is carried out there are certain error sources like the scale factor of the instrumentation (level and staff), the collimation error and the earth curvature, which can be considered as systematic and constant effects. Hence the deviation among repeatable height readings is concentrated on the repeatability of the measuring equipment and the refractive effects.

Considering the atmospheric air as the propagation medium of an electromagnetic beam the alterations on the refractive index is caused by the variations of the air density, which is in terms a function of the major meteorological parameters. The International Association of Geodesy has adopted empirical formulas which show that the refractive index is influenced by the wavelength, the temperature, the atmospheric pressure and the partial water vapor pressure (Ciddor 1996; Ciddor and Hill 1999; IUGG, 1999; Torge, 2001).

Assuming the visible electromagnetic spectrum, where the partial water vapor pressure effect is negligible (Breznikar and Aksamitauskas, 2012), for the needs of spirit leveling the well-known to geodesists local geodetic refraction coefficient k can be expressed by the following equation (Bahnert, 1972, 1978; Joeckel et al, 2008):

$$k = 502.7 \cdot \frac{P}{T^2} \cdot \left(0.0342 + \frac{dT}{dz}\right) \quad (1)$$

Where k = the geodetic refraction coefficient
P = the atmospheric pressure in mb
T = the temperature in °K
$\frac{dT}{dz}$ = the vertical temperature gradient in °K/m

By logging and differentiating equation 1 yields that the local geodetic refraction coefficient k is strongly dependent on the temperature gradient and is slightly dependent on the absolute air temperature and the atmospheric pressure (Brocks, 1939; Hirt et al, 2010; Torge, 2001; Wunderlich, 1985):

$$\frac{1}{k}\cdot dk = \frac{1}{P}\cdot dP - \frac{2}{T}\cdot dT + \frac{1}{0.0342+\frac{dT}{dz}}\cdot d\frac{dT}{dz} \quad (2)$$

In this paper the dependence among height readings, air temperature and atmospheric pressure is being investigated. Hence, both indoors and outdoors experimental tests were carried out by implementing a stand-alone set up of a high accuracy digital level and an air temperature sensor node mounted on the barcoded invar staff. Thus, the additional time series were generated, containing repeatable short term measurements of height readings, air temperatures and atmospheric pressures for a time period of several days and a time interval of 5 minutes. Moreover the repeatability of the digital level is being evaluated.

II. Data Acquisition

A. *Instrumentation and Stand-alone Set Up*

The geodetic instrumentation used in order to carry out the experimental tests and generate the corresponding time series was Leica DNA03 digital level, GPCL bar coded invar staffs and a heavy duty tripod. The stand-alone set up of the digital level was implemented by using a GEV 186 Y cable that ensured initially the uninterrupted power supply, by using a 12V external battery, as long as with the seamless data transfer, by online commanding of the digital level via an RS232 serial communication and the corresponding software (figure 1).

Figure 1. The automatic, stand alone and controlled set up of the DNA03 digital level.

The air temperature measurements were carried out by using a LORD MicroStrain TC-Link-LXRS sensor (figure 2) that was mounted on the invar staff at the same height as the level's telescope. This kind of sensor can be controlled wirelessly. Additionally the atmospheric pressure was acquired by using a Davis Vantage Vue weather station with a measuring accuracy of ±1mb. The station is placed at the same building where the experimental tests took place. Moreover a mobile weather station was used in order to convert the pressure readings to the desired mean altitude of the experiment.

Figure 2. The LORD MicroStrain TC-Link-LXRS sensor node [http://www.microstrain.com/wireless/tc-link-1ch].

Before the implementation of the experimental tests the digital level was checked at a local comparator while the reference scale of the temperature sensor was calibrated by using a climatic chamber device and the repeatability as well as the measuring accuracy was evaluated at ±0.1°C (Kampouris, 2018).

Regarding the outdoors experimental test and in order to secure proper lighting conditions during the night and assure the level's measuring ability a spotlight was used. The spotlight was placed at safe distance so that the air temperature sensor would not get heated, while an automatic operating mode was accomplished by using a timer switch (figure 3).

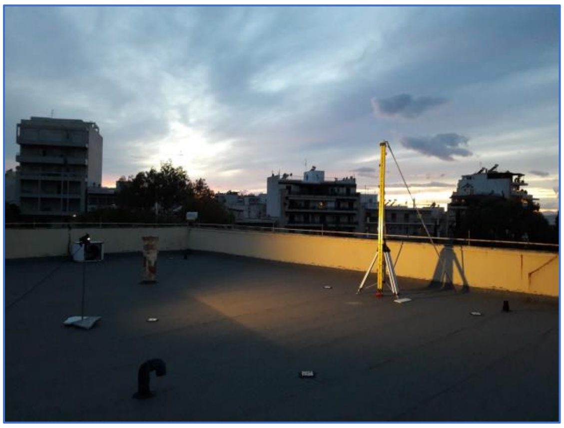

Figure 3. The spotlight and the3m invar bar coded staff just after sunset

B. *Generated Time Series*

After developing an automatic, stand alone and controlled set up there were three experimental tests that were carried out at the School of Rural and Surveying Engineering (SRSE) of the National Technical University of Athens (NTUA) in order to compute the dependence of the height readings and the meteorological parameters regarding spirit levelling measurements. Thus, the digital level that was deployed, was observing a bar coded invar staff. The height readings acquisition had a time interval of 5 minutes at a period of some days. Simultaneously to the height readings there were air temperature measurements taking place by using the air temperature sensor mounted on the invar staff.

Additionally the weather station was continuously generating time series of the atmospheric pressure. These measurements were then converted to the desired altitude with respect to the corresponding sampling measurements of the mobile weather station. The development of the aforementioned set up provided a synchronization of the different time series that was of the order of some seconds.

Thus, there were three experimental tests that were carried out two indoors and one outdoors at a sighting distance of about 25m, 50m and 40m respectively. The first test is not thoroughly presented in this paper because the trend lines of the measured parameters were completely stationary.

The fact that needs to be highlighted is that the meteorological conditions of the tests were chosen to be stable. This means that the ventilation and heating were switched off regarding the indoors experimental test while the part of the outdoors time series after sunrise (08:00) and just before sunset (17:00) were trimmed off and excluded from the computations. This happened in order to minimize the atmospheric turbulence fluctuations (which are increased indoors due to heating and ventilation and outdoors because of the heat flux due to convection) (Brunner & Kukuvec, 2011; Hirt et al, 2010).

These fluctuations except the height readings mainly affect the credibility of the air temperature measurements. Especially when the air temperature sensor is directly radiated by the sun, it gets heated and due to its thermal capacity the reliability of the measurements becomes questionable.

1) Indoors Set Up

The indoors experimental test was conducted at the basement tunnel of SRSE which is used for the metrological check and calibration of geodetic instrumentation (figure 4). The tunnel has a total length of about 50m.The digital level's measurements initiated at 2017-12-21 16:00:00 and ended at 2017-12-25 23:50:00, which is namely a total period of 4 days 7 hours and 50 minutes.

Table 1. The digital level's reading statistics of the indoors experimental test.

DNA Reading	Mean	St. Dev.	n/NA
Height	1.112146m	±65μm	1247/23
Distance	49.529m	±7mm	1247/23

The level's readings statistics are presented in table 1, where n is the number of the readings and NA is the number of the not available measurements.

Figure 4. the instrumentation set up of the indoors experimental test

The instrument height was developed and measured at 1.27m. The height readings of the indoors experimental test are graphically illustrated by a grey line in figure 5.

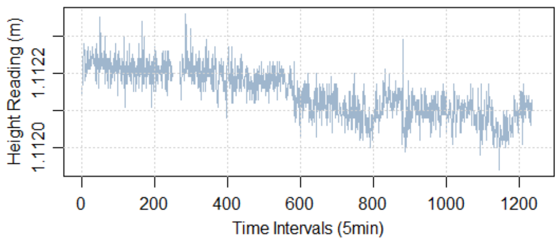

Figure 5. The height readings chart of the indoors experimental test at 50m.

The height readings present a slight cyclicality while they demonstrate a decreasing trend. Additionally the kernel density plot, which is presented in figure 6, indicates that there are two main values in the height readings time series.

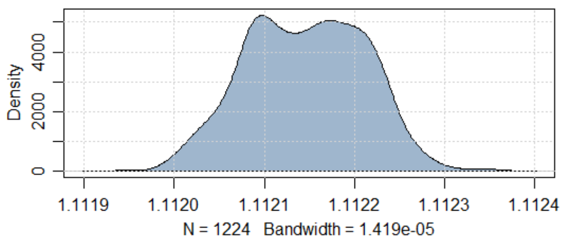

Figure 6. The height readings distribution of the indoors experimental test via a kernel density plot.

Figure 7 illustrates the air temperature sensors' readings, where also a decreasing trend with a pacing pattern is observed. Additionally figure 8 demonstrates the atmospheric pressure, which is decreasing during the first day and is increasing thereafter.

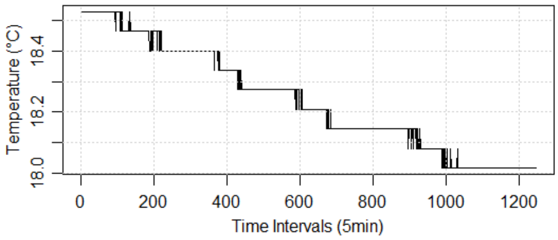

Figure 7. The air temperature sensors' readings of the indoors experimental test.

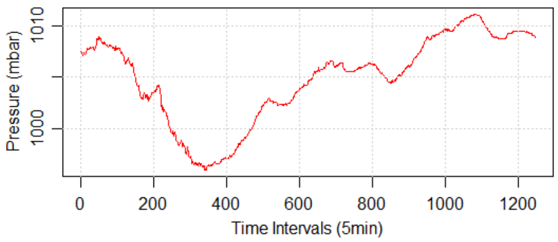

Figure 8. The pressure readings time series of the indoors experimental test.

2) Outdoors Set Up

The outdoors experimental test was carried out on the rooftop of SRSE. The only alteration to the previously conducted experiment is that a 3 meter bar coded invar staff was used. Moreover in order to secure proper lighting conditions during the night and assure the level's measuring ability a spotlight was used.

The overall instrumentation set up of the outdoors experimental test is presented in the figures 1and 3, where the horizontal distance between the level and the staff was a bit less than 40m.

The DNA03 readings of the second experimental test started at 2018-01-04 19:25:00 and ended at 2018-01-08 23:50:00, which corresponds to a total period of 4 days, 4 hours and 35 minutes with minor gaps among the measurements.

The height readings statistics, as they were finally trimmed, are presented in table 2. The instrument height was set and measured at 1.657m.

Table 2. The digital level's reading statistics of the outdoors experimental test.

DNA Reading	Mean	St. Dev.	n/NA
Height	1.633589m	±151μm	1206/440
Distance	37.949m	±6mm	1206/440

The following figure (9) demonstrates the height readings of the digital level for the outdoors experimental test. The trimmed parts of the height readings time series are plotted with red color. Moreover the height readings trend-line apparently shows cyclicality and an incrementing tendency.

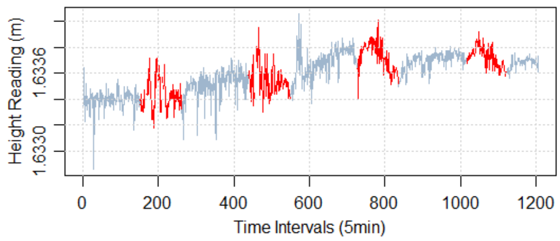

Figure 9. The height readings and the trimmed parts (red color) of the outdoors experimental test at 35m.

Additionally figure 10 represents as much as the initial as well as the final trimmed height readings distribution with red and grey color respectively. The number of the readings (N) and the smoothing bandwidth are referred to the trimmed readings. These two kernel density plots indicate that there are two to three main values contained therein the data

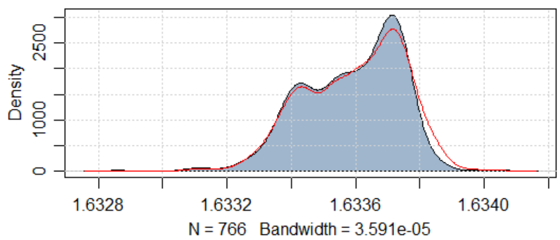

Figure 10. The initial (red color) and the trimmed height readings distribution of the outdoors experimental test via a kernel density plot.

Figure 11 illustrates the air temperature sensors' readings of the outdoors experimental test, where the hills correspond to the daylight part. In this graph the cyclicality between days is obvious but in general the temperature among the nights has an increasing tendency while the amplitude between the days is decreasing.

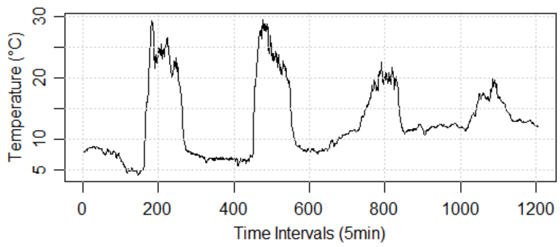

Figure 11. The air temperature sensors' readings of the outdoors experimental test.

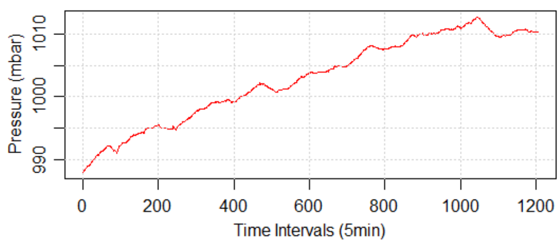

Figure 12. The pressure readings time series of the outdoors experimental test.

Additionally figure 12 demonstrates the pressure readings with respect to the outdoors experimental test where an upward trend is observed.

III. RESULTS

A. *Digital Level's Repeatability*

The repeatability of the digital level's measuring ability is computed through the standard deviation of each time series height readings with respect to the sighting distance. Pellegrinelli et al have demonstrated an empirical relationship in order to define the standard deviation of a single height reading with respect to the sighting distance (equation 3), by developing a motorization of DNA03 (Pellegrinelli et al, 2013).

$$St.Dev.(mm) = 0.001 \cdot Dist.(m) + 0.005 \quad (3)$$

where St. Dev. = the standard deviation of a height reading on an invar staff in mm
Dist. = the horizontal distance between the level and the staff in m

Thus they performed an automatic stand-alone set up which measured continuously for 8 days in an indoors tunnel. The time interval was defined at 5 to 6 minutes, while five invar staffs were mounted in different distances. Hence they generated about 2000 readings per sighting distance and a linear model was then fitted to the computed standard deviation values.

By the utilization of the aforementioned equation table 3 is constructed with regard to the three experiments that were previously discussed. Thus, the expected standard deviation (third column of table 3) is computed by the formula of equation 3 with respect to the sighting distance of each experiment.

The statistical significance of the difference between the measured and the expected value was then tested for a confidence level of 95%. According to the statistical tests the indoors experimental tests seem to be in accordance to the expected values and manage to pass the test while the outdoors experiment failed to pass it.

Table 3. The expected and the measured standard deviations of the digital level's height readings.

Exper.	Sight. Dist.	Expected	Measured	95%
Indoors	25.305m	±30μm	±29μm	Pass
Indoors	49.529m	±55μm	±65μm	Pass
Outdoors	37.949m	±43μm	±151μm	Fail

Additionally the manufacturer denotes that the standard deviation of the height readings average has to be less than ±700μm at a sighting distance of 20m (Leica, 2006). This means that the repeatability of the Leica DNA03 digital level is not static but is depended on the micrometeorology of the terrain, the environmental and lighting conditions (Kampouris, 2018).

A diploma thesis (Apodoulianakis, 2011) performed additional experimental tests with the Leica DNA03 at different lighting conditions and varying sighting distances. It is concluded that the slope of the linear model of equation 3 can range between 0.0038 and 0.0007, while the intercept can take either positive or negative sign values.

B. *Correlations of the Measured Parameters*

The dependence of the measured parameters was computed by using the Pearson and the Spearman correlation coefficients for their linear and monotonic relationships respectively.

Figure 13 demonstrates the Pearson correlation coefficients among the measured values of the indoors experimental test, where some strong (Height - Temperature) and moderate (Height - Pressure) correlations are noticed. This is not a general assumption but characterizes the particular dataset and is due to the trends among the different time series.

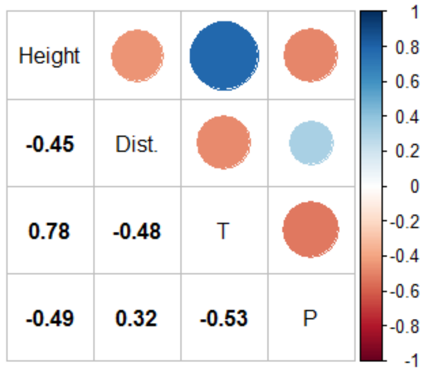

Figure 13. The Pearson correlation coefficients of the measured values of the indoors experimental test.

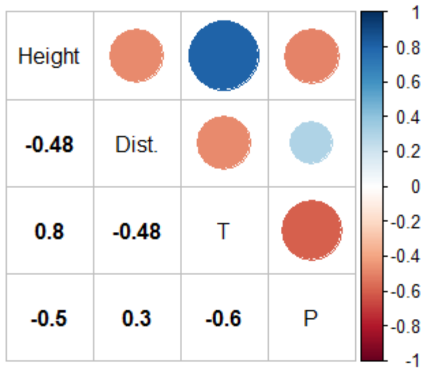

Figure 14. The Spearman correlation coefficients of the measured values of the indoors experimental test.

These Pearson correlation coefficients values came up because the height readings along with the temperature measurements are decreasing, forming a strong uphill linear relationship. While atmospheric pressure is increasing indicating a moderate downhill linear relationship with respect to the height readings.

Additionally the Spearman correlation coefficients of the outdoors experimental test (figure 14) do not indicate a noticeable difference with respect to the Pearson values. Even though that the correlations are slightly strengthened, regarding the parameters of interest.

The incrementing trends of the measured parameters of the outdoors experimental test, that have been noted earlier, interpret the strong (Height - Temperature) and moderate (Height - Pressure) Pearson correlation values that are presented in figure 15. Thus they indicate uphill linear relationships between height, pressure and temperature.

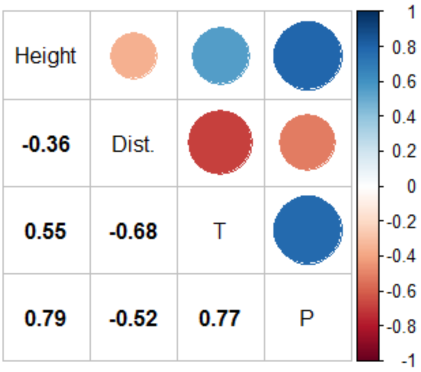

Figure 15. The Pearson correlation coefficients of the measured values of the outdoors experimental test.

The Spearman correlation coefficients that are demonstrated in figure 16 imply moderate and strong positive monotonic relationships among the parameters of interest. Again the Spearman correlation coefficients are slightly increased with respect to Pearson.

Figure 16. The Spearman correlation coefficients of the measured values of the outdoors experimental test.

IV. CONCLUSIONS

Initially, the influence of the meteorological parameters regarding the height readings time series is determined by the intense fluctuations of the outdoors experimental test. Moreover this view is reinforced by the fact that the repeatability of the digital level with respect to the external experiment failed to pass the statistical test.

Even the fact that both the experimental tests showed positive linear and monotonic correlations between the temperature and the height readings time series, this does not imply causation and further research needs to be made. This means that the computed correlation coefficients may only interpret the particular datasets. This means that the functional form of the influence of the atmospheric parameters regarding a single height reading seems to be neither linear nor monotonic.

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