Using IATS to Read and Analyze Digital Leveling Staffs

Andreas Wagner¹, Wolfgang Wiedemann¹, Thomas Wunderlich¹

¹ Chair of Geodesy, Faculty of Civil, Geo and Environmental Engineering, Technical University of Munich, Munich, Germany, a.wagner@tum.de, w.wiedemann@tum.de, th.wunderlich@tum.de

Abstract. It is possible to use modern total stations for leveling applications. Using digital staffs for relative height transfer gets a higher precision than using automatic target recognition (ATR) for prism detection. The study at hand describes the implementation to automatically read and analyze the code pattern of a digital leveling staff using an Image Assisted Total Station (IATS). The acquired 2-dimensional color image is converted into a binary signal and correlated with the a priori known reference signal. The result is used as initial value for a newly developed, alternative decoding method, in which the height differences of corresponding barcode edges are minimized. In different tests the precision and accuracy of our method is compared with the built-in ATR function of the total station as well as with a digital level. Standard deviations below 10 μm (1σ) prove comparable leveling capabilities of modern total stations – IATS.

Keywords: automatic level, barcode staff, digital leveling, height transfer, image assisted total station (IATS), leveling, leveling staff, monitoring.

1. Introduction

Almost all manufactures of total stations have instruments with built-in cameras in their product portfolio. These devices are commonly termed as Image Assisted Total Stations (IATS). Today, the images from the instruments’ cameras are used to support the field work procedures and for documentation purposes. The onboard processor and the implemented software are able to overlay the images as well as the live video stream with measurement and planning data or sketches. This is possible as the captured images are directly geo-referenced and orientated if the system is properly calibrated. In addition to the manufacturers’ usage and applications, the high resolution images taken by an IATS enable the development of new measurement approaches. Examples of such new applications fields are geo-monitoring [Reiterer et al. 2009, Wagner et al. 2014, Wagner 2016], Structural Health Monitoring [Wagner et al. 2013, Ehrhart & Lienhart 2015] or industrial metrology [Wasmeier 2009, Guillaume et al. 2012, Hauth et al. 2012]. We implemented the leveling capability into IATS as a further possible field of use, as described in the following. This is helpful e.g. for the high accurate transfer of the instrument height from a benchmark. It also extends the possibilities for
monitoring [Wagner et al. 2016] and can be seen as the next step towards a geodetic universal instrument [Wunderlich et al. 2014].

2. Digital Leveling

Leveling is still the most widely used method for relative height transfer of ground points. The measuring equipment comprises of a graduated staff and a level (instrument), which is basically a telescope that enables a horizontal line of sight, e.g. by a mechanical tilt compensator. Digital levels consist of additional electronic image processing components to automatically read and analyze digital (bar coded) leveling staffs, where the graduation is replaced by a manufacturer dependent code pattern. For first-order leveling or other high accurate engineering survey projects precise levels in combination with precise leveling staffs are used, which are stated with a standard error of $\leq \pm 0.5 \text{ mm}$ double-run leveling. Here, the code (modulation) information of the staff is usually engraved at an invar strip which has a low thermal expansion coefficient ($< 10^{-6} \text{ K}^{-1}$). To ensure high accurate results and/or as part of quality management system requirements, such as the ISO 9001, regularly inspections of the devices and the equipment are essential. National and international standards, e.g. DIN 18717 and ISO 12858-1, define parameters to be examined in periodical calibration. For invar leveling staffs these are, for example, the staff scale, the zero-point error, graduation corrections, and the thermal expansion coefficient. There are different calibration facilities, like the Geodetic Laboratory at the Technical University of Munich (TUM), which offer the parameter determination according to the mentioned standards [Wasmeier & Foppe 2006].

2.1. Staff code pattern

Various different code patterns exist for digital leveling staffs, as every manufacturer has developed its own modulation and analyzing method. The main reasons for this are patent rights to the individual solutions [Ingensand 1999]. Common to all versions is that a barcode is longitudinally imprinted on the leveling staff; the bars run transversely to the upright direction. The code pattern is converted into a digital intensity- and position-information via a CCD line sensor. Every implementation uses high contrast transitions (black-white or black-yellow) at the edges of the code-bars. At the moment, we implemented the code pattern used by the company Leica Geosystems in our approach, which is described in the following only. Here, an aperiodic pseudo-stochastic (binary) code sequence is used for encoding digital leveling staffs, which seems to be randomly composed. However, the code elements are arranged in such way that already short code sections are unique in the code sequence. The overall code is composed of black or white/yellow integer multiples of a $2.025 \text{ mm}$ wide base element. The widest occurring code element has the width of 15 elements, i.e. $30.375 \text{ mm}$. The entire code sequence is unique over a length of $4050 \text{ mm}$, which also defines the maximum extent of this type of leveling staffs [Ingensand 1999].
2.2. Demodulation

To decode the (Leica) code pattern into staff/height readings the pseudo-stochastic sequence must be known, resp. must be stored in the instrument. Two signals – the reference signal and the pre-processed image signal – are shifted stepwise against each other and each time the correlation coefficient is calculated. This value describes the statistical relationship between two random variables or two signals and has its maximum at perfect match. The overall correlation function $C_{pq}$ of the measurement signal $Q(y)$ and the reference signal $P(d, y - h)$ is [Ingensand 1990]:

$$C_{pq}(d, h) = \frac{1}{N} \sum_{i=0}^{N} Q_i(y) \cdot P_i(d, y - h) \quad (1)$$

From the maximum of this (two dimensional) function the desired distance $d$ resp. scale (ratio pixel/mm) and height $h$ can be derived. The position of the focus lens – determined by a displacement transducer or rotary encoder applied to the focus drive – provides a rough distance information as initial value. To speed up this process, especially for the levels of the first generation, the processing is split into a two-stage correlation, a coarse and a fine correlation.

3. Method

In engineering survey projects, it is often necessary to accurately determine the total station’s transit axis height. If the height is transferred from a benchmark, preferably a manual reading of a leveling staff should be used, instead of the less accurate reflector pole. To increase the reliability and accuracy of such a procedure a fully automatic digital reading and analysis would be desirable.

For this reason, we transferred the processing method of a digital level to a modern total station, resp. an IATS. The on-axis camera offers a comparable high magnification of the telescope and the on-board processor is meanwhile capable of simple image processing tasks. The main difference between both instrument types is that the telescope of the total station allows rotations in the vertical plane. In an automatic level, in contrast, a mechanical compensator ensures a horizontal sight for an approximately leveled instrument. The vertical angle of the total station is determined with respect to the plumb line, refined by an electronic inclinometer. This means, if the accuracy of the vertical angle reading is high enough, it is possible to level with a total station in the same way as with a leveling instrument.

However, due to practical reasons such as greater weight or much higher price of total stations, it is unlikely that levels will be replaced. But in some special applications it may be useful, e.g. to transfer the station height from benchmarks, as mentioned before. Further, it is possible to do non-horizontal sightings to leveling staffs and thus also cover large height differences with one single observation (with high accuracy). As we also have access to the (image) processing chain, we are able to consider additional special calibration parameters of the leveling staffs. As mentioned before, international and national standards specify periodical calibrations which determine adjustment parameters but these
are applied only occasionally. With our proposed decoding method, it is even possible to correct the graduation of each single code-bar without difficulties.

In the following sections we will first describe the new approach when using a total station instead of a level. In the second part [Section 3.2] the alternative decoding method will be presented.

3.1. Program sequence

The measuring procedure to read coded staffs by an IATS consists of several steps as shown in figure 3.1 and as described in the following.

![Figure 3.1 Program sequence to read and analyze a digital leveling staff using IATS](image)

For the data acquisition the leveled IATS must be manually aimed to the vertically aligned leveling staff (1). It is necessary that the vertical crosshair is centered on the leveling staff. During the further processing the image domain will be reduced to a small vertical stripe left and right of the crosshair. The vertical alignment is of minor relevance, as long as a few code-bars are visible in the image (that the code pattern is unambiguous). For the further processing the staff must be (2) focused either manually or by an integrated auto-focus of the total station. An additional reflectorless distance measurement (3) provides more accurate distance information as if it would be derived from the focus lens position (as done in digital levels). The horizontal and vertical angles are read out simultaneously with the image acquisition (4). In connection with the a priori determined camera calibration parameters the image is therefore fully orientated.

If the image is taken under a non-horizontal alignment ($\theta \neq 100$ $gon$ $\parallel V \neq 300$ $gon$) it is subjected to a perspective-based distortion, which has to be corrected by an image rectification (5). The distortion effect is a function of the camera location as well as its orientation in respect to the observed staff. As both parameters are known, the image can be transformed as it would look like as in a horizontal view. The rectification (projective transformation) can be expressed by a planar homography, as the code pattern on the leveling staff is present in a plane. For the further processing, the image is reduced to a small vertical stripe
which only contains the staff code pattern. The width of this region is automatically determined depending on the later measured distance to the staff. During the demodulation (6) the RGB information is transformed into an 8-bit grayscale, see figure 3.2. The pixels of each row are averaged, which effects a smoothing for noise reduction. The 1-dimensional signal is normalized, i.e. the intensities are stretched to the full 8-bit range (0-255).

Figure 3.2 Image pre-processing steps for the demodulation of the digital staff code pattern. The 2-dimensional RGB image section is converted stepwise into a binary signal.

To achieve faster processing the actual data analysis is separated into a coarse and fine correlation. (7) The initial value for the staff reading is calculated using 1-bit signals. Therefore, the normalized mean values are converted into binary values and state the measurement signal \( Q(y) \), c.f. equation (1). The correlation of \( C_{pq} \) is calculated by the XNOR-operator (exclusive NOT OR) of \( Q(y) \) and the shifted copies of the 1-bit reference signal \( P(y-h) \) as a function of the height \( h \). In our case, the distance \( d \) is fixed due to the high accurate determination by the electronic distance meter (EDM) of the total station, which gives

\[
C_{pq}(h) = \frac{1}{N} \sum_{i=0}^{N-1} Q(y) \oplus P_i(y-h)
\] (2)

In digital levels, in contrast, the correlation is extended to the second dimension, by taking the distance into account. In both cases, the result of the function has a clear visible peak in the correlation coefficients which specifies the offset of both signals and finally the corresponding staff reading.

The fine optimization (8), implemented in digital levels, uses the previous results as starting values for a second correlation. This time the full 8-bit intensity information of the input signal is used. Likewise, the step width of the shift in distance \( d \) and height \( h \) is decreased to refine the results of the correlation procedure. In our case we replaced the fine correlation by a new processing approach, as described in the next section.
When using a total station instead of a level a further final height
determination step (9) is necessary. The staff reading, i.e. the result of the fine
correlation or the alternative approach must be corrected by the influence of the
non-horizontal alignment. This trigonometric height difference $\Delta h$ can be
calculated by the vertical angle $\zeta$ and the measured horizontal distance $d$ or slope
distance $s$ using:

$$\Delta h = d \cot \zeta = s \cos \zeta$$  \hspace{1cm} (3)

An additional correction for curvature and refraction may also be applied.

### 3.2. Alternative decoding method

An alternative approach to the fine correlation of both signals is to minimize
the height differences of corresponding barcode edges, related to the
implementation used in the Zeiss DiNi level series. The image of a leveling staff
is processed with a subpixel edge detection algorithm to extract linear features at
each code element transition. We implemented an approach based on Burns et al.
[1986] but modified to our needs, in which similar gradient directions are grouped
into potential line regions. If certain thresholds – regarding size and shape of the
regions – are met, a line is fitted through each group by least squares estimation,
weighted by the gradient magnitudes. The result is a vector with measured
barcode positions $E_M$ in image coordinates. The visible code sequence of the
reference gives a vector $E_R$, in which each element represents the distance of a
black and white transition (and vice versa) from the zero point of the staff. Both
vectors are connected by a scale factor $s$ and a translation, resp. height
difference $h$:

$$E_R = s \cdot E_M + h$$  \hspace{1cm} (4)

We solve this equitation system with the least squares method, by
minimizing the distance of corresponding edges. The results of the coarse
correlation are used as the initial values. The pairwise assignment is determined
by a forward and backward search of nearest neighbors in both vectors. A distance
filter and an outlier test remove (remaining) lines which may be caused by failed
edge detection or partial occlusion of the observed code pattern. The adjustment
is performed iteratively to ensure a correct assignment of corresponding edges.

The classical fine optimization, which is implemented in digital levels (of the
company Leica), is a two-dimensional correlation where the two parameters scale
(distance) and height have to be solved iteratively. The correlation function,
equation (1), has to be calculated in two processing loops step by step with
slightly changed parameters to find the maximum correlation coefficient. In our
approach the same parameters are solved in a linear equitation system directly
which leads to a faster computation. Only a limited set of iterations is used for
the correct edge assignment and outlier removal. The additional time for the
necessary image processing is negligible.
4. Experiments

To investigate the performance of our approach we conducted several tests which are described below. All tests were performed indoor in a laboratory under controlled atmospheric conditions. The digital leveling staff used is a 2 m length invar staff from Leica, the IATS a Leica Nova MS60. The telescope camera has a resolution of 2560 × 1920 pixel with a respective size of 2.2 × 2.2 μm. The image is magnified 30-times by the telescope optics, which gives a field of view of 1.5° (1.67 gon). One pixel on the image sensor corresponds to an angular value of 0.61 mgon. The angular accuracy (horizontal and vertical) is specified with 1” (0.3 mgon), the accuracy of the reflectorless distance measurement is listed with 2 mm + 2 ppm [Leica Geosystems 2015].

4.1. Precision

In one experiment the repeatability of measurements with our approach is investigated. In a static setup both, the Leica MS60 and the barcode staff, are installed on pillars in the laboratory with unknown, but constant height offset. The horizontal distance between the instrument and the invar staff is ~15.5 m. Over a time period of 3 hours we take 400 images and process them with the algorithm described in the previous sections. To compare and monitor the instrument’s behavior over time, we also take 400 measurements with the built-in automatic target recognition (ATR) of the instrument to a co-operative prism next to the leveling staff. For both time series the vertical angle is nearly 100 gon (horizontal aiming). All measurements are reduced by the mean value of their time series. The height deviations calculated from the staff readings are shown in figure 4.1. A standard deviation of 0.008 mm (1σ) is obtained for height observations derived from barcode staff readings with a maximal deviation from the mean value of 0.029 mm. This is slightly better than the ATR measurements with a standard deviation of 0.012 mm (1σ) and a maximum deviation from the mean value of 0.039 mm.

To ensure the repeatability of the height readings in different barcode sections we run additional tests. In a static setup of instrument and digital leveling staff we take 15 images under different vertical angles showing independent barcode segments that should result in the same height offset between the total station and the leveling staff. This test was repeated 6 times (90 independent measurements). Due to the changing vertical angles the results are influenced by the additional trigonometric height differences, i.e. by the uncertainty of the angle and distance measurements. The mean standard deviation within the 6 sets of the height readings is 0.015 mm (1σ) with a maximum absolute deviation from the mean value of 0.038 mm.
Figure 4.1 Result of 400 IATS staff readings at a fixed height difference in a distance of \(~15.5~m\). Residuals to the mean value (left) and probability distribution function fitted through the histogram of the sample data (right)

4.2. Accuracy

To obtain the accuracy of our method, we used a different setup. On the one side we compare the results with a commercial precise digital level, on the other side with a measuring system of higher order. The leveling staff is installed in the vertical comparator of the TUM Geodetic Laboratory, allowing a controlled stepwise vertical movement of the staff. We simulate small displacements of 0.05 mm, the same as it occurs e.g. in subsidence surveys. The single increments are measured by the IATS (Leica MS60) and a precise digital level (Leica DNA03), both instruments are built up in a distance of \(~5.1~m\), and are referenced by a high accurate laser interferometer (Hewlett Packard 5518A, \(~1~\mu m\)).

Figure 4.2 Comparison of IATS (left) and digital level (right) height readings with the interferometer reference. The digital staff is displaced in 0.05 mm steps (for better visibility only a part of the data is displayed)
Figure 4.2 shows the heights values of the interferometer plotted against the IATS heights (left) and against the digital level (right). In total 100 increments are measured, for better visibility only a part of the data is displayed. Both data sets show similar behavior. The standard deviation of both residuals is $0.006 \, mm$ (1σ), the maximum deviations to the interferometer value are $0.016 \, mm$ (IATS) and $0.019 \, mm$ (level).

5. Discussion

The presented experiments are based on distances of $5 \, m$ and $15 \, m$ – limited by the dimensions of our laboratory. Even though, they can be seen as a proof of concept of the IATS leveling capabilities. The first test scenarios demonstrate that the developed algorithm allows to repeat height readings from a digital leveling staff with high precision. Compared to the ATR function of the total station even slightly better results can be reached. In case of non-horizontal views, the standard deviation increases marginal as the trigonometric part is additionally influenced by the uncertainties of the angle and distance measurement. In the second test scenario, we compared our method with measurements of a precise level and references of a laser interferometer. The simulated height deviation can be detected with equivalent high accuracy. This means there is no significant difference in the results using either a precise level or an IATS for leveling.

In first additional measurements in $20 \, m$, $30 \, m$ and $40 \, m$ distance we achieve results with no significant differences to those of a digital level (direct comparison of height readings IATS – digital level) [Lichtenberger 2015]. The detailed results will be published in future.

6. Conclusion

In many use cases it is important to precisely transfer the instrument height of a total station from a reference point. Up to now this has often been done by manual reading from a leveling staff on a benchmark. In this paper we show the capability of modern total stations (with built-in in telescope cameras) to solve this task with high accuracy by automatic readings. With the presented method for decoding digital barcode staffs – based on subpixel edge detection and least square adjustment – an efficient on-board application can be implemented. The results obtained by IATS are competitive with those of modern digital levels.

The possibility of a non-horizontal aiming is the biggest advantage of leveling with an IATS. It allows to handle large height differences between the instrument and the staff. However, these measurements are influenced by uncertainties in the vertical angle reading and distance measurement. This is also possible using the built-in ATR function, but as shown, we get a slightly better object/code pattern detection. In combination with the more accurate leveling staff instead of a reflector pole, the final result will be improved. Further, by using a leveling code pattern it is impossible to do (manual) misalignments, as the vertical aiming of the crosshair to the barcode is not necessary. This is e.g. useful in monitoring applications where repetitive measurements to the same target(s) need to be done.
In contrast to level instruments also multiple targets in different heights can be surveyed.

The presented analysis method to read digital leveling staffs with total stations is highly versatile. Next to the already mentioned monitoring tasks, like bridge load tests or subsidence measurements, methodology applications, such as the examination of linearity or machine alignments, are also possible.

In the future we will integrate additional code patterns. We are optimistic that such a basic leveling function will be implemented by the manufacturers in upcoming total station firmware. The hardware is ready now.

References


Očitanje i analiza digitalne nivelmanske letve pomoću mjerne stanice s ugrađenim CMOS senzorom

Sažetak. Da li je moguće koristiti moderne mjerne stanice za niveliranje. Korištenje digitalnih nivelmanskih letvi za prijenos visina omogućuje preciznije mjerenje nego korištenje automatskog prepoznavanja signala (ATR) za detekciju prizme. Članak opisuje implementaciju automatskog očitanja i analize uzorka barkoda digitalne nivelmanske letve pomoću mjerne stanice s ugrađenim CMOS senzorom (IATS). Dobivena 2-dimenzionalna slika se pretvara u binarni signal i korelira s „a priori“ poznatim referentnim signalom. Rezultat se koristi kao inicijalna vrijednost za novo razvijenu, alternativnu metodu dekodiranja, u kojoj se visinske razlike pripadajućih rubova barkoda minimiziraju. U različitim ispitivanjima preciznost i točnost ove metode je uspoređena s ugrađenom ATR funkcijom mjerne stanice i digitalnim nivelirom. Standardna odstupanja ispod 10 μm (1σ) dokazuju mogućnost niveliranja pomoću modernih mjernih stanica – IATS-a.

Ključne riječi: automatsko niveliranje, digitalno niveliranje, mjerne stanica s ugrađenim CMOS senzorom (IATS), monitoring, niveliranje, nivelmanska letva, nivelmanska letva s barkodom, prijenos visina.

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