Deformation Analysis of Tripods under Static and Dynamic Loads

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SUMMARY

The deformation of tripods may significantly affect high precision measurements. Therefore it is necessary to have profound knowledge about the effect of static and dynamic loads (magnitude and temporal progress). This may be e.g. vertical deformations or torsions induced by mounting a tacheometer and executing automatic measurement processes. The effects are dependent on the stability of these ‘accessories’, which often are provided in a wide bandwith by the manufacturer, starting from a lowcost tripod up to a highend tripod for industrial measurements.

This study investigates the effect of static and dynamic loads on different types of tripods and shortly outlines the reasonable application in relation to different measurement tasks and accuracy requirements. The work is a cooperation between TU Vienna and Leica Geosystems AG. For a priori theoretical simulations a Finite Element model of a tripod is created to design the experimental investigations. Because of the complexity of the mechanical system, the model is firstly restricted to the simulation of vertical static loadings.

For the investigations of height stability, different sensors are evaluated. Considering measuring accuracy and capability for automatisation, it is decided to use a Leica DNA03 (digital level) to measure the vertical deformations. The determination of torsional effects and horizontal drift is performed by an electronic collimator from Leica with a sampling rate of 16 Hz. This sampling rate also enables the detection of dynamic effects as a result of tacheometer movements. The measurements are applied to autocollimation mirrors, mounted on the tripods. It is shown that the tripod deformations are not negligible if high precision results are required.

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1. INTRODUCTION

Monitoring of deformation processes and control measurements in industry demand highest requirements for the stability of the tacheometer adaptation. In many cases, no fixed pillars or consoles are available and the sensor has to be mounted on a tripod. In this case, the temporal stability of the tripod is an essential precondition to obtain accurate measuring results. Accurate means the minimization of random and systematic errors that are induced by possible movements of the tripod head. In this context, tripod stability means as well height stability (Δz) as horizontal stability (Δx, Δy) and must be referred to the whole length of the measurement process. Of course, the above statements are not only valid for mounted tacheometers but also for precise levelling instruments (esp. Δz) or GPS antennas.

Besides external disturbances like wind, sun, humidity, instability of the soil and soil vibrations, the system tripod ⇔ tacheometer is also affected by the tacheometer itself. A modern robot tacheometer widely automatically performs the measurement process by motor-driven tacheometer axes. The tacheometer mass (e.g. 5.5 kg, Leica TCRP1201) and its accelerations (up to rotational speeds with 128 gon/s, Trimble S8) respectively decelerations induce static and dynamic loads on the tripod which may lead to elastic or (in the worst case) to plastic deformations. Consequently, the sensor design of a measurement process must not be restricted to the tacheometer properties but also includes the knowledge about the interaction between tacheometer and tripod.

In the last years, some investigations of tripod deformations have been carried out (e.g. Ingensand, 2001 and Depenthal, 2004). As reaction to the increasing numbers of different tripod types available on the market, a cooperation between TU Vienna and Leica Geosystems AG was established to investigate and evaluate the properties of different Leica tripods and competitive products in combination with standard robot tacheometers and test procedures. One focus is set on the introduction of new materials like fibreglass in tripod manufacturing (e.g. S40 from Nanjing Survey or Trimax from Crain Inc.). The investigations are primarily concentrated on static vertical loads and the height stability of the tripod head respectively quasi-static drift reactions. In addition, the applied methods of deformation monitoring also enable the detection of dynamic deformation processes in a low frequency range up to 8 Hz. The following presented results are obtained within the framework of a diploma thesis (see Nindl, 2006).

2. THEORETICAL SIMULATIONS

In a first step theoretical simulations for tripod stability are performed to find out the range of static vertical deformations to be expected and to make a decision for a suitable monitoring system which is able to detect these quantities. The software RSTAB (see Dlubal, 2009) is used to create a simple Finite Element model (FE-model) of the tripod. The FE-model abstracts each tripod leg as a system of three homogenous and isotropic parts (upper part with two beams, overlap and lower part with one beam) with rigid connection. The three legs are connected in a single knot which represents the tripod head. The tripod itself is fix supported by the non-elastic ground (see Figure 1a). One main neglect is given by the missing clamps at the tripod legs. Consequently, the model can only give a rough first impression of the deformations.

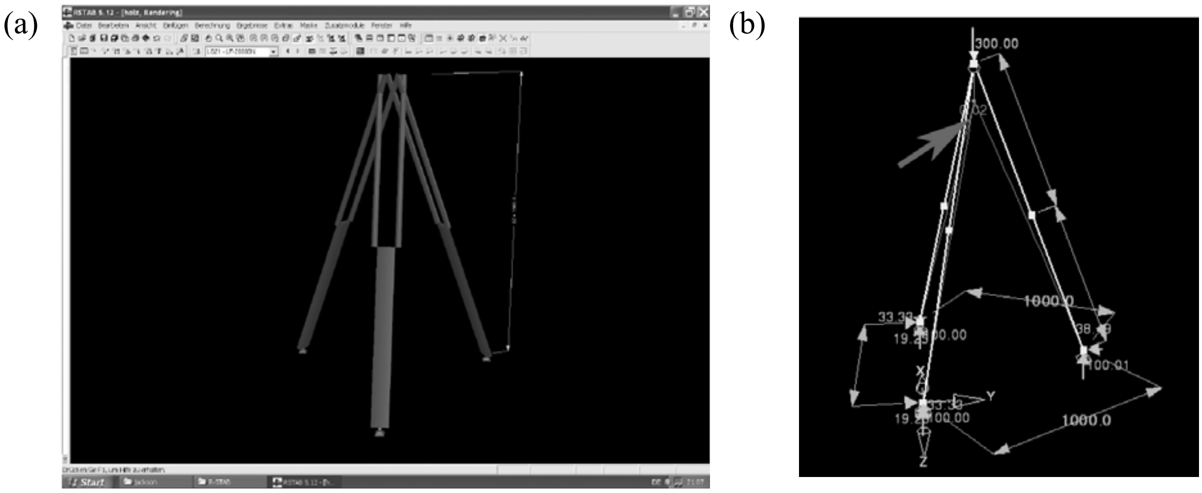

Figure 1: FE-model of a tripod created with RSTAB

The geometrical parameters (e.g. leg length and cross section) are derived from a Leica GST 120-9 tripod, which is classified as ‘heavy tripod’ and normally tested with loads up to 30 kg. The Young’s modulus *E* is derived from dry hardwood.

The tripod head is loaded with a typical test mass of 30 kg which complies with a vertical acting force of ca. 300 N (see Figure 1b). As a static reaction the tripod head (knot) performs a vertical displacement of $\Delta z = 0.02$ mm. By comparison with empirical data obtained in Section 3 ($\Delta z_{\text{meas}} \approx 0.02 - 0.03$ mm), the FE-model calculations can be proofed and the model be assumed as realistic. The calculation of the failure load results in ca. 240 kg.

The calculation results give a good first impression about the quantity of static deformations and are used in Section 3 to design a suitable monitoring system.

3. TRIPOD DEFORMATIONS UNDER STATIC LOADS

3.1 Application of vertical static loads

All following investigations are realized in a lab at Leica Geosystems AG in Heerbrugg / Switzerland. The lab allows to establish constant environmental conditions by minimization of changes in temperature and humidity. Other possible external disturbances like soil movements can be excluded. For the application of static vertical loads, a special experimental setup is created which consists of a cable pull system with test weight for controlled loading and a digital precise levelling instrument (Leica DNA03) to monitor the vertical tripod deformations (see Figure 2).

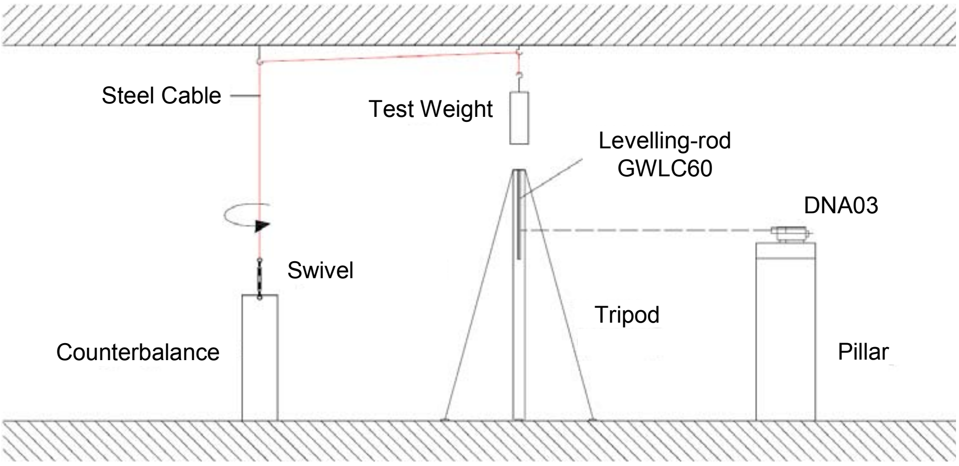

Figure 2: Experimental setup for the investigation of static vertical tripod deformations

Counterbalance and swivel allow a smooth lowering of the test weights (brass-barrels which simulate the different loads) on the tripod. The resulting vertical deformations are indicated by the vertical displacements of a short precise levelling-rod (Leica GWLC60) which is fixed at the main screw of the tripod head (see Figure 3). The levelling instrument DNA03 is specified with a mean km-error of $\sigma_{\Delta h} = 0.3$ mm. Preliminary investigations show that repetition measurements with positive correlations on a small cutout of the levelling-rod achieve accuracys with $s_{dh} < 0.01$ mm for small height changes. This accuracy requires the decay of possible compensator oscillations of the DNA03 and restricts the measuring frequency to max. 0.25 Hz. The measurements are automatically logged and transferred to a PC. To create reproducible test conditions, the tripod legs are fully extended and equally spaced on the ground with 1 m distance. The clamps are reproducible tightened with a torque spanner.

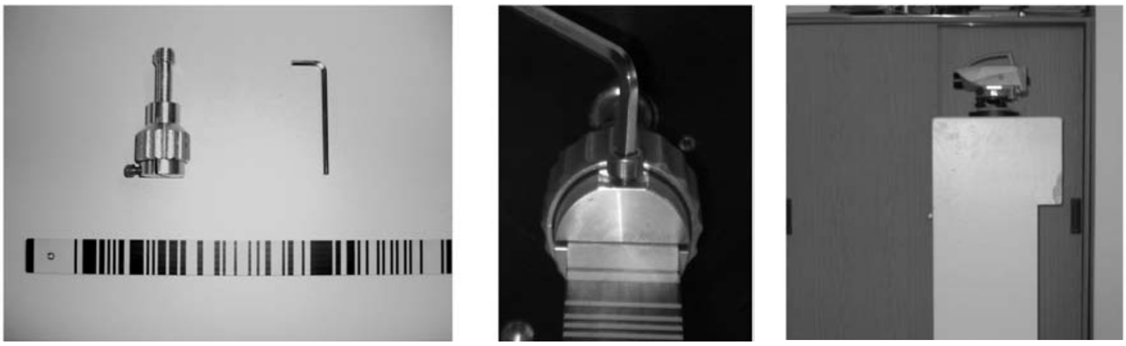

Figure 3: Adaptation of the precise levelling-rod GWLC60 and DNA03

3.2 Investigation results for different types of tripods

The applied static loads vary between 10 kg for light tripods (classification ‘L’) and 30 kg for heavy tripods (classification ‘H’) and are conform with the typical test procedures at Leica Geosystems AG. According to ISO12858 (1999), the maximum admissible vertical deformation for tripods is $\Delta z_{\max} = 0.05$ mm. This boundary represents one basic requirement for the inner stability of the tripod system. The investigated tripods are

- GST120-9 (H): Leica, wood (beech)
- S40 (H): Nanjing Survey, fibreglass
- Trimax (H): Crain Inc., fibreglass
- CTP101 (H/L): Leica, wood
- GST05 (L): Leica, wood (pine)
- GST05L (L): Leica, aluminum
- CTP103 (L): Leica, aluminum

In Figures 4 and 5 two typical time series for vertical deformation processes are shown. Both are for heavy tripods (wooden tripod Leica GST120-9 and fibreglass tripod Crain Trimax) with a vertical loading of 30 kg. The measuring frequency is 0.25 Hz ($\Delta t = 4$ s).

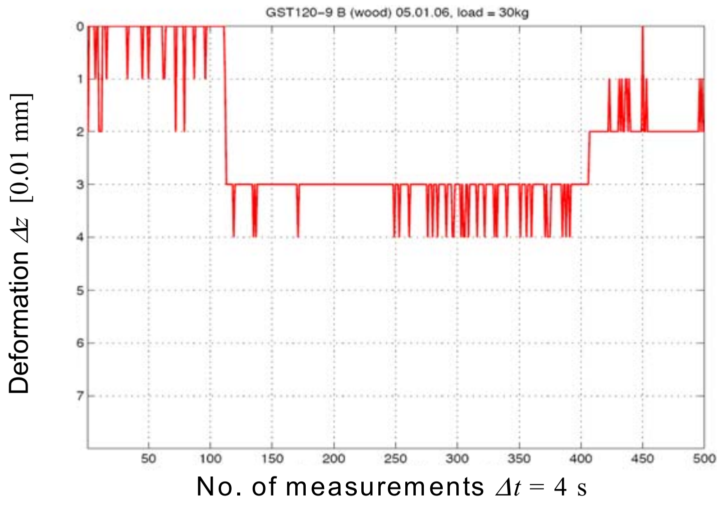

Figure 4: Wooden tripod Leica GST120-9 loaded with 30 kg

The measurement process starts monitoring the non-loaded tripod (110 measurements ≈ 7 min). After this the load is (slowly) applied to the tripod head and remains there for ca. 20 min. This is a typical value specified by experts for the expected period of possible height changes. After this, the tripod is unloaded again and monitored for further 6-7 min. The peaks are induced by the DNA03 itself which has a maximum resolution of 0.01 mm.

After loading, the head of the wooden GST120-9 quickly performs a vertical movement of $\Delta z \approx 0.03$ mm (see Figure 4) and remains in a new balanced state. The increasing number of peaks from measurement 250 to 400 could be an indicator for a very small overlaid trend. After unloading, the tripod quickly relaxes but keeps a hysteresis between $\Delta z = 0.01\text{-}0.02$ mm which could be induced by the tripod clamp. In total, it can be stated that the deformation remains in the admissible range.

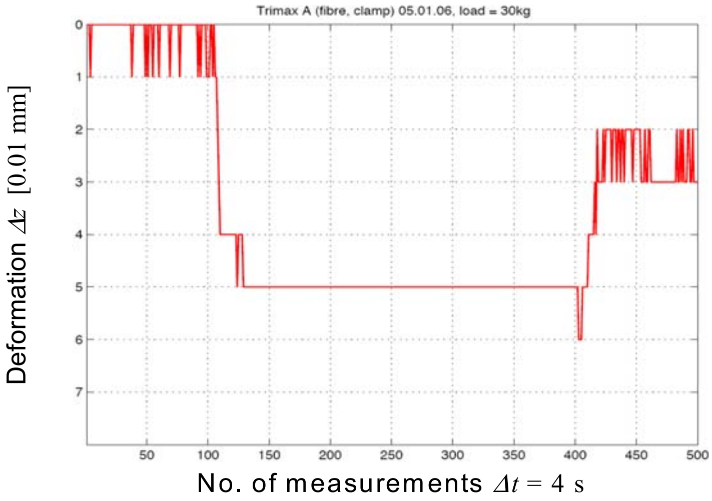

Figure 5: Fibreglass tripod Crain Trimax loaded with 30 kg

In comparison with the GST120-9, the head of the fibreglass Trimax performs a significant larger vertical movement with $\Delta z \approx 0.05$ mm (see Figure 5), which is barely admissible. The hysteresis is between $\Delta z = 0.02\text{-}0.03$ mm. This shows clearly that concerning mechanical loads, the construction of the fibreglass tripod is less stable than the wooden one. This statement must be referred to the whole tripod system, this means properties of the monolithic parts and connections (e.g. clamps). With the existing experimental design, a separation is not possible. The results from all tripod investigations are presented in Table 1.

Table 1: Investigation results for height stability (H = heavy tripod ; L = light tripod)

Tripod	Company	Material	Test load [kg]	Vert. def. Δz [0.01 mm]	Boundary ISO12858 [0.05 mm]	Hysteresis [0.01 mm]
GST120-9 (H)	Leica	Wood (beech)	30	3	OK	1.5
S40 (H)	Nanjing Survey	Fibreglass	30	4	OK	-2
Trimax (H)	Crain Inc.	Fibreglass	30	5	OK	3
CTP101 (H/L)	Leica	Wood	30	3	OK	1
GST05 (L)	Leica	Wood (pine)	10	1.5	OK	0
GST05L (L)	Leica	Aluminum	10	3	OK	1
CTP103 (L)	Leica	Aluminum	10	2	OK	0.5

In the table it is shown that all tripods fulfill the ISO requirements for vertical height stability. As mentioned before, the fibreglass tripods in the H-classification obtain somewhat worse results than wood. After loading, all tripods show no significant vertical drift and remain in a nearly balanced state. Hysteresis after unloading is restricted to max. 0.03 mm.

Referring to a measurement process, the investigated vertical deformation properties of the tripods can be evaluated as acceptable, even for high precision requirements. The applied experimental loads are significantly higher than normal tacheometer loads and the detected deformations nevertheless in a range of only some hundredth mm. The quick movement to a nearly balanced state creates a stable position (better than 0.01 mm) of the tripod head during the actual execution of the measurements. The influence of the hysteresis is only relevant if the instrument is demounted and remounted again during the progress of the measurements (using the tripod in the sense of a forced centering). But it must be emphasized that these statements are only valid for a pure static vertical loading and the absence of external disturbances (e.g. soil vibrations).

3.3 Investigation of quasi-static tripod deformations

Regarding high precision measurement processes, a more critical influence is represented by a possible horizontal torsion of the tripod head. The torsion directly influences the orientation of a tacheometer and induces random and systematic errors in the measured horizontal directions. It can be divided in a long-term quasi-static drift (‘horizontal drift’) and short-term effects, which are created by the tacheometer movement (torsional rigidity under dynamic loading, see Section 4).

One main reason for the horizontal drift is the continous decomposition of stresses in the tripod as a result of tripod setup (e.g. disparate clamping) and tacheometer mounting. To investigate this effect, a new monitoring system is used which consists of a Leica autocollimator and a autocollimation mirror (see Figure 6).

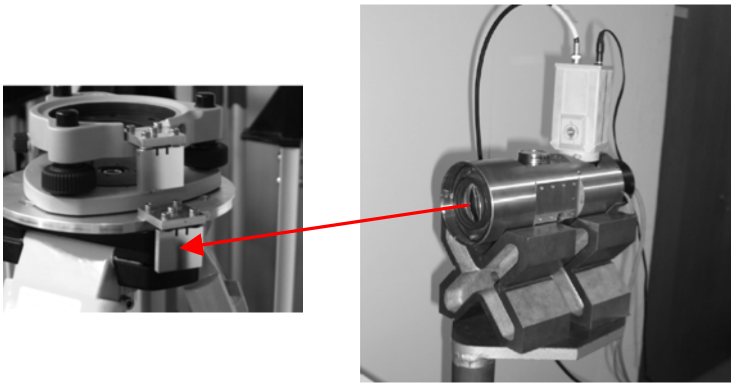

Figure 6: Leica autocollimator and mirror for the detection of small tripod rotations

The mirror is fixed at the tripod head and performs the same movement. The autocollimator is fully automated and has a maximum measuring frequency of 16 Hz. The integrated PSD

(= Position Sensitive Device) enables the detection of the mirror rotations with an expected accuracy $\sigma_\theta < 2^{cc}$.

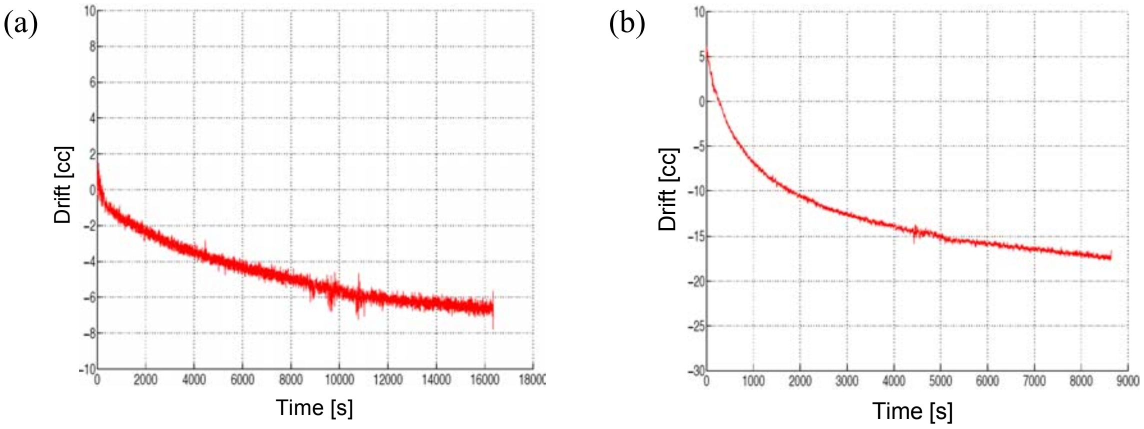

Figure 7: Monitored horizontal drift of (a) GST120-9 and (b) S40 (only cutout)

For the drift investigations, all selected heavy and light tripods (see Section 3.2 and Table 2) are loaded with the same tacheometer Leica TCA2003 (weight ≈ 8 kg). This is a typical instrument for precise engineering survey. During the monitoring process, the tacheometer is not moving and the load is static. Two representative examples of horizontal drift behaviour are shown in Figure 7. The total observation time is between 2 and 5 hours. The wooden tripod GST120-9 (H) shows a convergent behaviour with a total drift of $\Theta \approx 6.5^{cc}$ after 4.5 hours. For many applications, the drift within the first 15 minutes is also a relevant quantity. With $\Theta_{15} \approx 1.5^{cc}$, it is within the range of the measuring accuracy of the TCA2003 ($\sigma_r = 1.5^{cc}$). According to the specified admissible boundary of $\Theta_{\max} = 8^{cc}$, the total drift can also be evaluated as noncritical. In comparison with the GST120-9, the fibreglass tripod S40 shows a significant higher torsion. After 15 minutes, the drift is $\Theta_{15} \approx 7^{cc}$ and after 5 hours, the total drift converges to $\Theta \approx 22.5^{cc}$. According to measuring accuracy and admissible boundary, these quantities must be considered in the design of the measurement process.

Table 2: Results of horizontal drift investigation

Tripod	Company	Material	Total drift [cc]	Drift after 15min [cc]	Boundary [8^{cc}]
GST120-9 (H)	Leica	Wood (beech)	6.5	1.5	OK
S40 (H)	Nanjing Survey	Fibreglass	22.5	7	NO
Trimax (H)	Crain Inc.	Fibreglass	9	8	NO
CTP101 (H/L)	Leica	Wood	4	1.5	OK
GST05 (L)	Leica	Wood (pine)	3	0.5	OK
GST05L (L)	Leica	Aluminum	23	15	NO
CTP103 (L)	Leica	Aluminum	9.5	2	NO

The results of all investigated tripods are shown in Table 2. It is obvious that in comparison with fibreglass and aluminun, wood shows the best drift properties.

4. TRIPOD DEFORMATIONS UNDER DYNAMIC LOADS

4.1 Application of dynamic loads

The effect of dynamic loads (e.g. torques induced by tacheometer accelerations and decelerations) is also an important target goal for the investigation of tripod deformations. In the following, the combination of autocollimator and autocollimation mirror (see Figure 6) is again used for monitoring. It must be emphasized that the restricted measuring frequency of the autocollimator (16 Hz) is not really suitable for dynamic processes like vibrations. Nevertheless, some first results can be obtained and will be discussed in the following section.

Loaded by a rotating tacheometer, the horizontal torsional rigidity is an important criterion for the evaluation of tripod stability. It describes the resistance of the tripod against horizontal torsions induced by torques (in particular torsional moments, e.g. Böge, 2006). It mainly depends on geometry (e.g. cross sections) and material (Young's and shear moduli) of the tripod components. Typical Leica tacheometers (e.g. TCA2003) achieve rotational speeds up to 50 gon/s. Within the acceleration and deceleration phases they create horizontal torques up to M_T = 56 Ncm. The magnitudes of the torques are restricted by a friction clutch.

The interesting question is now, if the torsional rigidity of a tripod is able to compensate tacheometer movements or not. If not, the resulting horizontal torsion of the tripod head may influence the orientation of the tacheometer and creates random and systematic errors (see also Section 3.3).

4.2 Investigation of dynamic tripod deformations

The experimental setup again consists of different types of tripods (see Section 3.2 and Table 3) with a mounted tacheometer TCA2003. In comparison to Section 3.3, the tacheometer is now moving. It performs an automatic set measurement to two diametrically arranged prisms P1 and P2. The prisms are measured in the sequence:

P1 in face 1 (P1') => face 2 (P1'') => P2 in face 2 (P2'') => face 1 (P2')

In Figure 8 the monitoring results of the horizontal torsion are presented for the wooden tripod GST120-9. The different peaks (maximum amplitudes of horizontal torsion) clearly indicate the different tacheometer actions:

- Single peaks are created by manual actions on the tacheometer keyboard (e.g. start of set measurement) or accelerations (negative peak) respectively decelerations (positive peak) in the tacheometer rotation.
- Double peaks are created as reaction to the beginning of a change of face (chof) of the tacheometer.

All peaks show a similar magnitude between $\Delta\theta \approx \pm(3\text{-}5^{cc})$. With the current monitoring design, a significant influence on the accuracy of horizontal directions cannot be detected as normally the measurement process shortly starts after the peak event. For more detailed investigations, a higher temporal resolution and a better correlation between torsions and horizontal circle readings are required. Taking into account the accuracy of the autocollimator (see Section 3.3), the variations between the peaks are not significant.

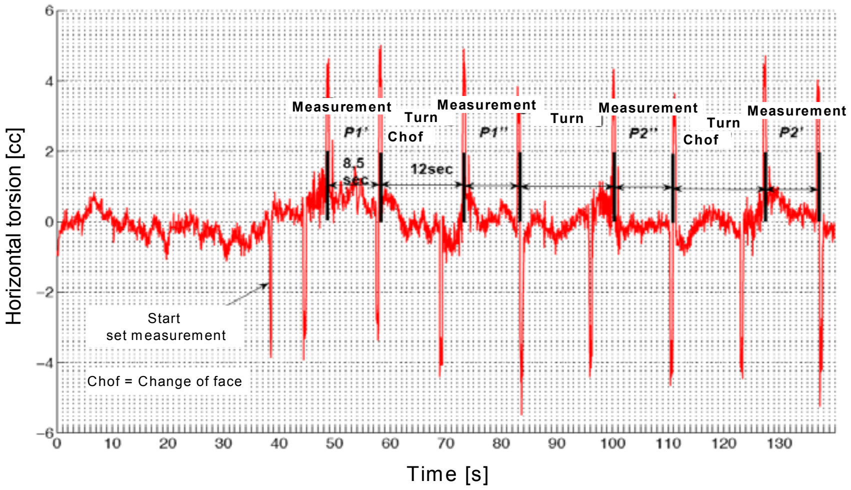

Figure 8: Horizontal torsion of tripod GST120-9 during dynamic loading with TCA2003

Figure 9 shows the comparison between two different tripod materials: GST120-9 (wood) and Trimax (fibreglass). Both tripods are loaded with the TCA2003 which performs an automatic set measurement. It is obvious that the fibreglass tripod gets larger peaks (up to $\Delta\theta \approx 15^{cc}$) than the wooden tripod ($\Delta\theta \leq 10^{cc}$). The main reason for this are the good damping properties of wood in comparison to the refractory fibreglass.

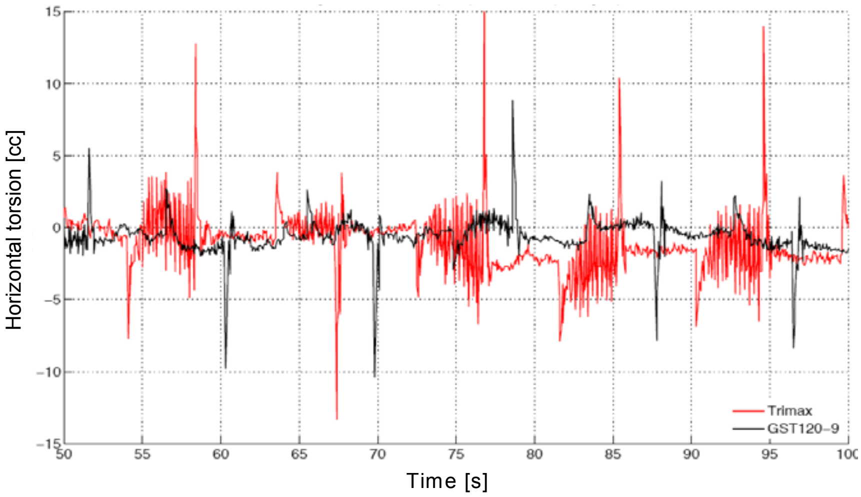

Figure 9: Comparison of torsion: wooden tripod (GST120-9) and fibreglass tripod (Trimax)

The mean peak-values for all investigated tripods are shown in Table 3. To get comparable results, the experimental setup is the same for all different types.

Table 3: Mean peaks as reaction to TCA2003 movements (+ clockwise ; - counterclockwise)

Tripod	Company	Material	$\Delta\Theta_{mean}$ (+) [cc]	$\Delta\Theta_{mean}$ (-) [cc]
GST120-9 (H)	Leica	Wood (beech)	6	-6
S40 (H)	Nanjing Survey	Fibreglass	6	-6
Trimax (H)	Crain Inc.	Fibreglass	9	-8
CTP101 (H/L)	Leica	Wood	6	-5
GST05 (L)	Leica	Wood (pine)	17	-18
GST05L (L)	Leica	Aluminum	15	-15
CTP103 (L)	Leica	Aluminum	7	-8

As a first rough result it can be stated that the light tripods generally perform larger torsions than heavy tripods (except CTP103). This effect seems to be independent of the material and is obviously correlated with the pure mass distribution in the system tripod ⇔ tacheometer. Within a tripod class (H or L) the mean values show no significant differentiation (except again CTP103). But as shown in Figure 9, extreme values may have significant differences dependent on the tripod material.

5. CONCLUSIONS AND OUTLOOK

The experimental setups for the investigation of static and quasi-static tripod deformations can be evaluated as suitable and obtain significant results. All results and discussions are related to the system tripod ⇔ tacheometer and neglect possible external disturbances like soil vibrations, sun, etc.

The height stability of all tested tripods fulfills the ISO requirements and enables the application in standard and precise measurement processes. No significant vertical drift can be detected. Possible hysteresis effects should be considered in the case of demounting and remounting of a tacheometer (forced centering scenario).

Horizontal drift effects must be considered as well in standard as in high precision measurement processes. In comparison with fibreglass and aluminum, wood shows the best properties with the lowest movements. Taking into account the specified measuring accuracy for horizontal directions of typical tacheometers in engineering survey ($< 5^{cc}$), the drift has a significant influence and always requires the periodical control of the orientation by stable reference points. If available, long-term measurement processes should be realized on pillars or stable wall brackets.

Some first impressions concerning the influence of dynamic effects are obtained. The tripod reactions to tacheometer actions like accelerations and decelerations can be clearly detected.

But the used monitoring system is not suitable to detect high-frequency deformations. The experimental setup makes it impossible to separate possible hysteresis effects after the dynamic tripod ‘peak’-reaction from the overlaid drift. This task requires further investigations in balanced working points (concerning static and quasi-static loadings). A more detailed investigation of the dynamic effects with a self developed laser measurement system and measuring frequencies up to 30 kHz is currently performed in a further diploma thesis (Grubinger, 2009).

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