# High Frequent Total Station Measurements for the Monitoring of Bridge Vibrations

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**Abstract.** Robotic total stations (RTS) are frequently used for the measurement of temperature induced bridge deformations or during load testing of bridges. In experimental setups, total stations have also been used for the measurement of dynamic bridge deformations. However, with standard configurations the measurement rate is not constant and on average an update rate of 7-10Hz can be achieved. This is not sufficient for the vibration monitoring of bridges considering their natural frequencies which are also in the same range. In this paper, we present different approaches to overcome these problems.

In the first two approaches we demonstrate how the measurement rate to prisms can be increased to 20Hz to determine vertical deformations of bridges. Critical aspects like the measurement resolution of the automated target tracking and the correct sequence of steering commands are discussed.

In another approach we demonstrate how vertical bridge vibrations can be measured by using an image assisted total station (IATS) and corresponding processing techniques. The advantage of image-based methods is that structural features of a bridge like bolts can be used as targets. Therefore, no expensive prisms have to be mounted and access to the bridge is not required.

All approaches are verified by laboratory investigations and their suitability is proven in a field experiment on a 74m long footbridge. In this field experiment the natural frequencies derived from the total station measurements are compared to the results of accelerometer measurements.

**Keywords.** robotic total station, image assisted total station, bridge monitoring, vibration monitoring, target tracking

## 1 Introduction

Today's bridge monitoring is either based on the measurement of displacements or the measurement of vibrations. Displacement measurements are important during load tests and can also be used to assess the long term behaviour of bridges. In contrary, vibration measurements focus on the determination of the natural frequencies. These characteristic frequencies change in case of temperature changes or damages. Until recently geodetic sensors were only capable of displacement monitoring and other sensors like accelerometers had to be used for vibration monitoring.

Within the last decade the resolution and measurement rates of geodetic sensors has been improved significantly and new sensors like ground based interferometric radar have been developed. As shown by Lienhart and Ehrhart (2015), modern geodetic sensors can be used for static and dynamic bridge monitoring. This article demonstrates in detail how the measurement rate of a standard total station can be increased to be capable of dynamic monitoring. It is furthermore shown that cameras integrated in total stations can be used as sensors for dynamic bridge monitoring.

## 2 Automated Measurements with Robotic Total Stations

Modern robotic total stations (RTS) are multi sensor systems which determine three dimensional coordinates of target points by combining horizontal angle (Hz), vertical angle (V) and distance (d) measurements.

Robotic measurements require automated targeting systems which can find and track prisms. Such systems send out infrared light and detect the position of the reflected signal either by a camera sensor (CCD or CMOS array) or by a quadrant detector. One example of an automated targeting system is the automated target recognition (ATR) system of Leica Geosystems. Since the TPS1200+ series the ATR sensor is a CMOS array (Bayoud, 2007) where one pixel corresponds to an angular resolution of approximately 3mgon. When measuring to a prism the position of the prism center on the CMOS array is detected. In a next step the deviations $ATR_{Hz}$, $ATR_V$ from the line of sight are calculated. If these deviations are within a certain threshold, the offset is added to the raw angle readings $Hz_{raw}$, $V_{raw}$ of the angle encoders. Otherwise the telescope is repositioned to aim at the target more precisely. Finally, the readings of the tilt compensator in sighting axis ($l_{comp}$) and orthogonal to it ($t_{comp}$) are taken into account. Therefore, the displayed angle readings are given by:

$$Hz = Hz_{raw} + \mathrm{ATR_{Hz}} + \mathrm{t_{comp}} \cdot \cot \mathrm{V} \quad (1)$$

$$V = V_{raw} + \mathrm{ATR_V} + \mathrm{l_{comp}} \quad (2)$$

The measurements of four different sensor types are used to calculate one target position. These sensors are:

- Angle encoders
- ATR sensor
- Tilt compensator
- EDM sensor

For dynamic monitoring the measurement frequency and measurement resolution of each sensor is of importance.

## 3 Limitations of Dynamic Monitoring with Robotic Total Stations

Psimoulis and Stiros report about laboratory investigations and case studies using a Leica TCA 1201 robotic total station for dynamic bridge monitoring (e.g. Psimoulis and Stiros, 2007, 2008, 2011). The main limitation according to their research is the low and non-equidistant measurement rate of about 7Hz of the total station. We verified their findings in our measurement laboratory using a Leica TS15 I 1” R1000 total station (serial: 1613987, firmware: 5.60) and a Leica GPR1 circular prism. The instrument was controlled by a computer using the GeoCOM protocol. The connection to the computer was established with a serial cable and a baud rate setting of 115 200 was used. After the total station locked onto the prism, continuous distance measurements were started and angle, EDM and tilt measurements were read using the GeoCOM command 2167 (TMC_GetFullMeas) with a wait time of 5000ms.

Figure 1 shows the frequency distribution of 1000 consecutive measurements. It can be seen that most measurements were made with a frequency of 7 to 10Hz which is in accordance to the findings of Psimoulis and Stiros (2007).

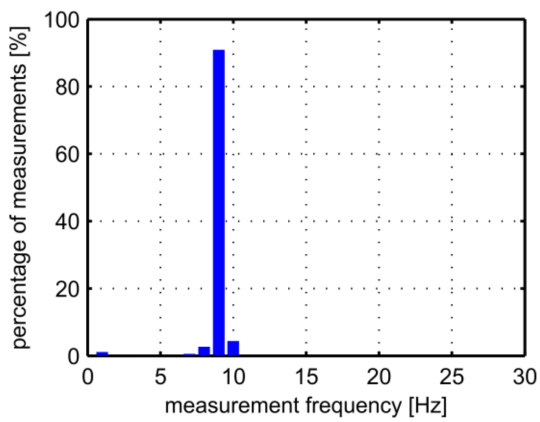


**Fig. 1** Distribution of measurement frequency of 1000 distance and angle measurements using a Leica TS15 total station locked onto a prism

Considering the Nyquist theorem only natural frequencies of less than 4.5Hz can be detected with such a measurement rate. This is not sufficient for many bridges because the critical natural frequencies can also be higher (e.g. Heinemeyer et al., 2009, p. 10).

## 4 High Frequent Total Station Measurements

In order to increase the measurement frequency and also the measurement resolution we used three different approaches.

### 4.1 Approach A: Angle Only Measurements

The limiting sensor for high frequent measurements is in many total stations the EDM sensor. However, to measure bridge vibrations it is often not necessary to measure the distance to the target continuously. With the right orientation of the total station to the bridge it can be sufficient to perform an initial distance measurement at the beginning and then continuously measure movements orthogonal to the line of sight using the ATR sensor. The initial distance measurement can then be used to convert the recorded angle changes into displacements. Figure 2 shows two examples of total station positions. At position I the angle measurements are mainly sensitive to vertical and lateral movements whereas at position II the main sensitivity is in vertical and longitudinal bridge direction.

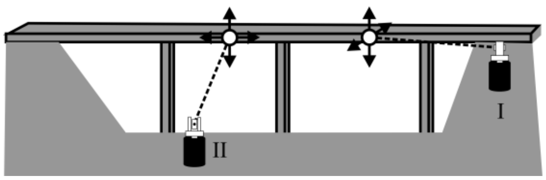


**Fig. 2** Examples of total station positions for dynamic angle based bridge monitoring

In order to demonstrate the improvement in the measurement frequency we again used the Leica TS15 total station with the same cable, baud rate settings and the same computer. The instrument was locked to the target but without making distance measurements. Since no distance measurements are available a different GeoCOM command has to be used. We used the command 2003 (TMC_GetAngle1). It is important to note that this command delivers ATR corrected angles only when the instrument is locked to the target. It cannot be used for single ATR measurements. Figure 3 shows that without distance measurements the measurement frequency increases to about 20Hz.

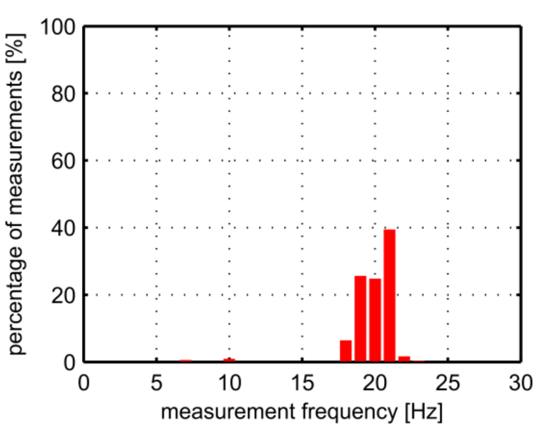


**Fig. 3** Distribution of measurement frequency of 1000 ATR corrected angle measurements using a Leica TS15 total station locked onto a prism

It is important to note the only pure angle GeoCOM commands (like TMC_GetAngle1) have to be used when locked onto a target but not performing distance measurements. When the command 2167 (TMC_GetFullMeas) is used without continuous distance measurements the measurements are returned at a high rate (about 30Hz) but cannot be used because not real measurements are delivered.

We also determined the measurement resolution of the total station in continuous tracking mode. Therefore, the prism was mounted on a motorized linear positioning stage (Figure 4) which moved the prism orthogonal to the line of sight at approximately constant speed.

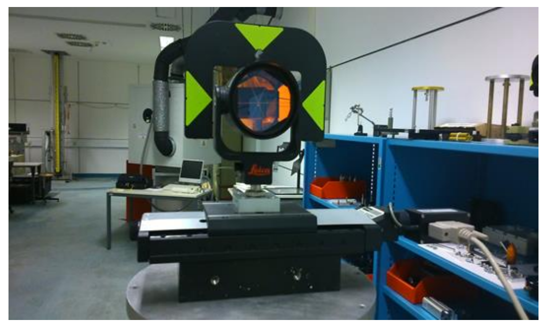

**Fig. 4** Leica circular prism mounted on a motorized linear positioning stage (Physik Instrumente M-410.DG)

The measured horizontal angular changes are displayed in Figure 5. It can be clearly seen that the quantization of the ATR corrected angular readings is 0.3mgon. This corresponds to the angular resolution of 1/10 of a pixel of the CMOS array.

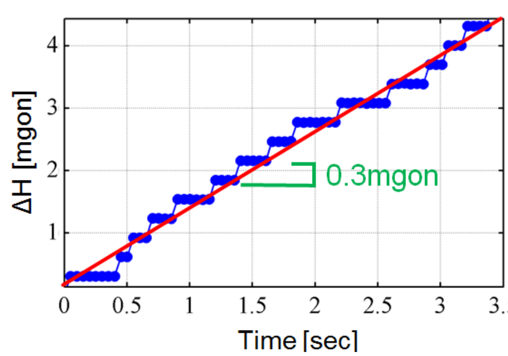


**Fig. 5** Quantization of dynamic angle readings with ATR corrections of a Leica TS15

It is important to note that the resolution is even worse when older instruments like the Leica TPS1200 instrument series are used. Dynamic ATR angels of these instruments are delivered only with a resolution of 1 pixel. This can cause problems in dynamic monitoring application as is shown in Lackner et al. (2016). In static monitoring this problem does not occur because the resolution of static ATR measurement of a Leica TS15 is 1/100 of a pixel (i.e. 0.03mgon).

## 4.2 Approach B: Instrument with Higher EDM Rate

Since the main limitation of standard robotic total stations for dynamic deformation measurements is the measurement rate of the EDM sensor, an obvious approach is to use a total station which is capable of high frequent EDM measurements. Examples of such instruments are the MS50 or MS60 Multi Stations of Leica Geosystems. These instruments are capable of EDM measurement frequencies with up to 1000Hz in scanning mode.

In order to assess the measurement performance when tracking a prism we also performed the laboratory experiments with a Leica MS60 I R2000 (serial: 882001, firmware: 1.30). As with the TS15, the instrument was locked onto the prism, continuous distance measurements were started and angle, EDM and tilt measurements were read using the GeoCOM command 2167 (TMC_GetFullMeas) with a wait time of 5000ms.

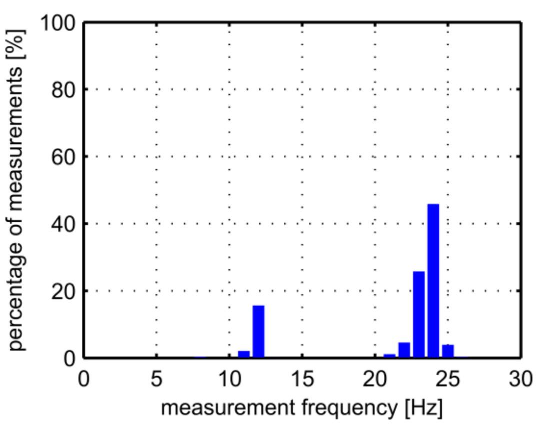


**Fig. 6** Distribution of measurement frequency of 1000 distance and angle measurements using a Leica MS60 total station locked onto a prism

It can be seen in Figure 6 that the measurement frequency is most of the time between 21 and 25 Hz. It also looks like that sometimes one measurement is missed and therefore a second frequency group of 11 and 12Hz exists.

Several aspects are important to mention at this point:

<u>Type of cable and communication settings</u>

- The measurements shown in Figure 6 were performed with a serial cable and a baud rate of 115 200.
- We also performed measurements using a USB connection and gained similar results.
- Using a lower baud rate than 115 200 significantly reduces the measurement frequency.

<u>GeoCOM command parameters</u>

- It is important to understand the meaning of the parameter *waittime* of the GeoCOM command 2167 (TMC_GetFullMeas). The instrument always sends a reply as soon as new measurement data is available. The parameter waittime only defines the maximum time to wait for a new measurement. A wrong setting of the waittime is for instance 0ms. Although it seems that the measurement rate is suddenly significantly higher (30Hz or more) the instrument does not deliver real measurement values. It does not have enough time to complete the measurements and sends the same measurement value several times. In order to avoid this we used a waittime of 5000ms and therefore giving the instrument enough time to send a valid reply.

<u>USB converters</u>

- The results shown in this paper used direct serial or direct USB connections without adapters. We also performed experiments using a serial cable and different serial to USB converters to connect the cable with the computer. We noticed that the measurement frequency significantly dropped when using some converters.

We also tested the approach A using only angle measurements with the command 2003 (TMC_GetAngle1). When using a TS15, the measurement frequency improved significantly, however when using the MS60 the opposite effect occurred. Suddenly the measurement frequency dropped to 10Hz, see Figure 7.

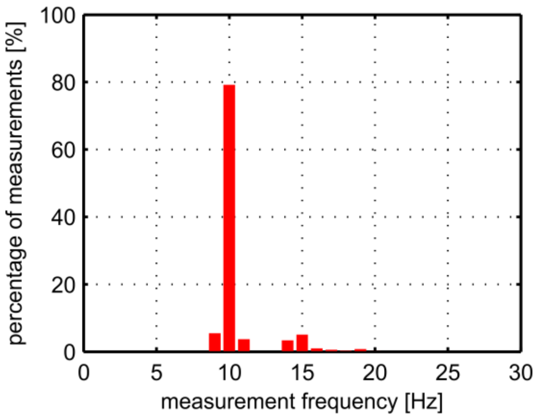


**Fig. 7** Distribution of measurement frequency of 1000 angle measurements using a Leica MS60 total station locked onto a prism and the GeoCOM command 2003

When we perform dynamic monitoring with the MS60 (firmware: 1.30) we therefore use continuous distance measurements and the command 2167 with an appropriate waittime (e.g. 5000ms).

Although measurement frequencies of angles and distances of more than 20Hz can be achieved with the MS60 the limitation of the ATR resolution of 0.3mgon remains. In order to increase the resolution it would be necessary that the ATR would also deliver angle corrections with a resolution of 1/100 pixel in dynamic measurements. A different approach to increase the resolution is to use an image sensor with higher pixel resolution. Such an image sensor could be an integrated on-axis camera.

### 4.3 Approach C: Image Based Measurements

The MS50 and MS60 total station have integrated overview and on-axis cameras. The images of these cameras are captured with a CMOS array with a size of 2560px x 1920px. As described in Ehrhart and Lienhart (2015a) video streams can be recorded with a frequency of 10Hz (MS50) or even higher (MS60). Our calibration showed an angular resolution of about 0.61mgon/px. This is significantly better than the angular resolution of the ATR camera (3mgon/px). We demonstrated in laboratory investigations that the position of markers can be detected with a precision of 0.1mgon (Ehrhart and Lienhart, 2015b). A further advantage of image based measurements is that no prisms have to be mounted on the bridge. Obviously, light conditions are critical and measurements are not possible in complete darkness. One way to perform vibration measurements also at night is to use light emitting targets as demonstrated by Bürki et al. (2010) or Wagner et al. (2013).

## 5 Field Experiment

Additionally to the laboratory experiments we also verified the approaches A and B in a field experiment. We chose the Augarten footbridge (steel construction, 74m span width, 4.5m roadway width) in Graz, Austria as a test bed (Figure 8). The bridge was equipped with accelerometers to obtain reference values for the frequencies in the bridge oscillations. We furthermore attached a prism for the RTS measurements and circular targets for the IATS measurements to the bridge. By using natural features on the monitored structure (such as the area around the nut bolts in Figure 8), the IATS measurements are also possible without any artificial targets. Table 1 lists the used sensors and their measurement frequencies.

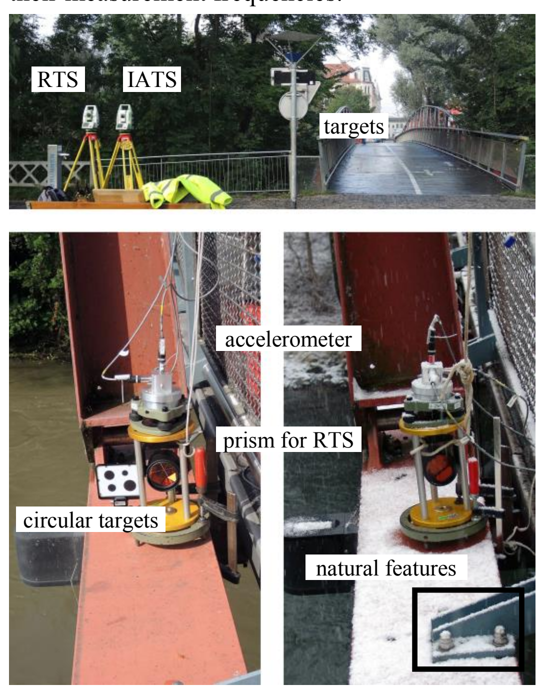


**Fig. 8** Experimental setup with RTS and IATS (top) and accelerometers and targets attached to the bridge (bottom row).

**Table 1.** Used sensors for measuring bridge vibrations

| Sensor | Name | Meas. freq. |
|---|---|---|
| IATS | Leica MS50 1" R2000 | 10Hz |
| RTS | Leica TS15 I 1" R1000 | 20Hz |
| Accelerometer | HBM B12/200 | 200Hz |

In a first experiment, the bridge was excited by a single walker (Figure 9). The amplitude of the oscillation is about 1mm which is similarly measured by the RTS and the IATS. Although the IATS has a lower measurement frequency than the RTS (cf. Table 1), the frequency response resulting from the IATS measurements is much more in correspondence to the accelerometer measurements.

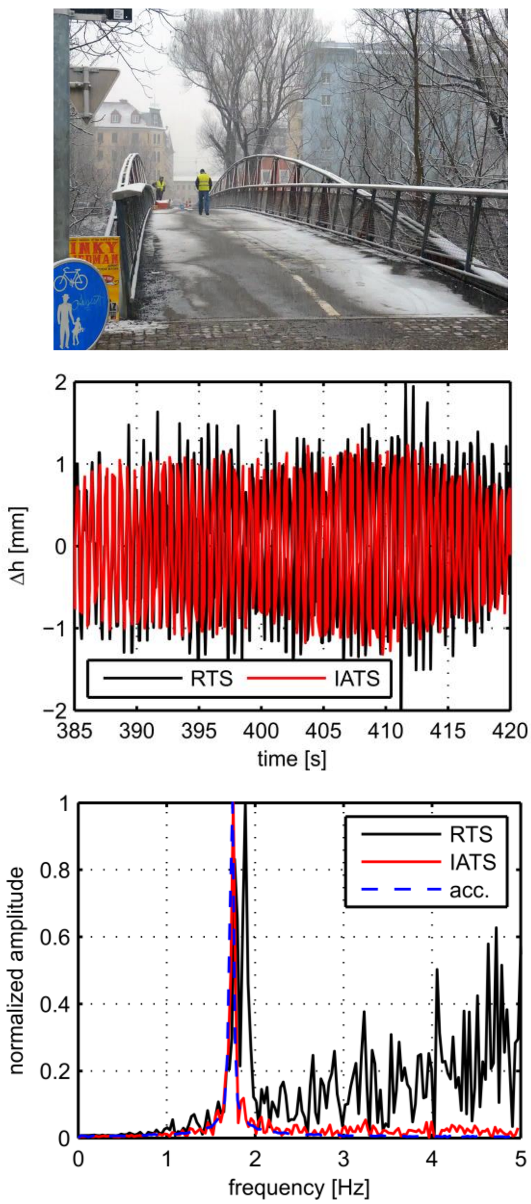


**Fig. 9** Excitation of the bridge by a single walker (top) and resulting height variations (middle) and frequency responses (bottom). Distance of IATS and RTS to respective targets: 33m. IATS observed natural features.

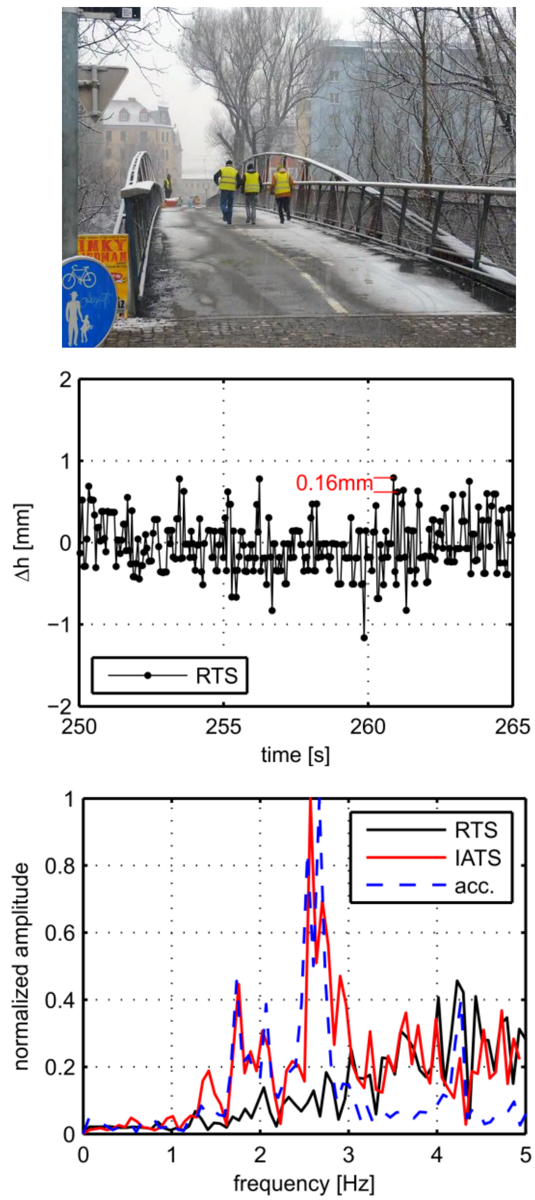


**Fig. 10** Excitation of the bridge by three runners (top) and resulting height variations (middle) and frequency responses (bottom). Distance of IATS and RTS to respective targets: 33m. IATS observed natural features.

To correctly identify the frequency of an observed oscillation, the used measurement system must meet the following conditions: 1) the sampling theorem must be fulfilled and 2) the measurement system must be sensitive to the amplitude of the oscillation.

For oscillations with frequencies below 3Hz and a measurement frequency of 20Hz, the RTS measurements clearly fulfil the sampling theorem. However, the sensitivity of the RTS measurements in tracking mode is problematic for oscillations with small amplitudes. This is emphasized by a second experiment where the bridge was excited by three runners (Figure 10). The RTS measurements show a discretization of about 0.16mm at a distance of 33m which corresponds to 0.3mgon resolution of dynamic ATR measurements (cf. Section 4.1).

Compared to Figure 9, the amplitude of the oscillation is much smaller in Figure 10. Consequently, the shape of the observed oscillation is much more disturbed by the discretization of the measurements and a determination of the dominant frequency is not possible from RTS measurements. The IATS measurements are again in good correspondence to the reference values gained from accelerometer measurements.

In a final experiment, the bridge was exposed to a quasi-static loading caused by a vehicle driving over the bridge at a low velocity (Figure 11). The movement of the bridge deck caused by this event is similarly detected by RTS and ITAS measurements. Note that the apparent measurement noise in Figure 12 in fact represents high-frequent oscillations of the bridge deck such as in Figure 9.

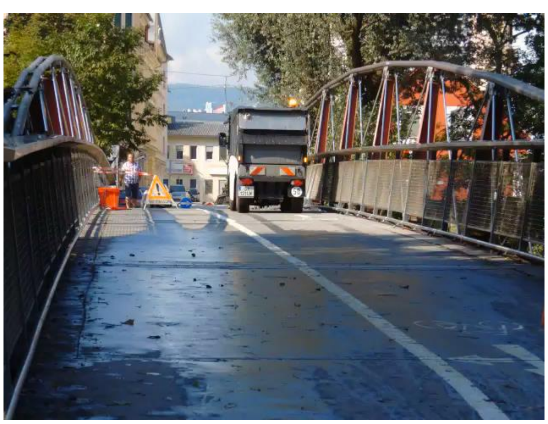

**Fig. 11** Excitation of the bridge by a vehicle

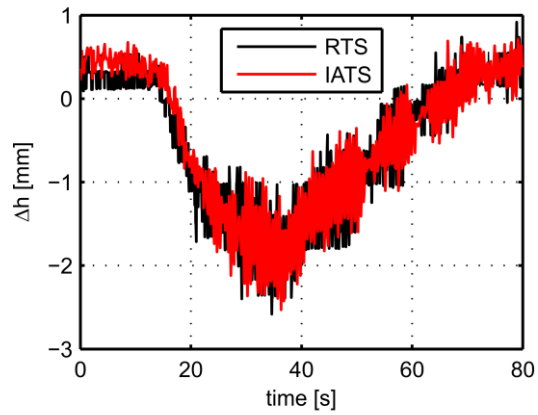


**Fig. 12** Height variations due to vehicle crossing over the bridge. Distance of IATS and RTS to respective targets: 39m. IATS observed circular targets.

## 6 Summary and Conclusions

Up to date total stations could not be used for dynamic monitoring of bridges due to the low measurement frequency of 7 to 10Hz of the instruments. In this article we presented several methods to increase the measurement frequency of commercially available total stations.

In the first approach angle only measurements were performed when the instrument was locked to a prism. By using ATR corrected angle measurements without dynamic distance measurements the measurement frequency of a standard Leica TS15 robotic total station could be increased to about 20Hz. It has to be mentioned that angle measurements are only sensitive to movements orthogonal to the line of sight. With the right orientation of the setup point to the bridge the vibrations in the desired bridge directions can be observed. The measured angle changes can also be converted into displacements if an initial distance measurement is performed.

In a second approach an instrument with a higher EDM measurement rate was used. When using a Leica MS60 Multi Station dynamic angle and distance measurements to a prism are possible with more than 20Hz.

In both approaches it is critical to

- Use the right GeoCOM commands. Angle only commands (e.g. 2003 (TMC_getAngle1) if no distance measurements are made and commands with distance measurements (e.g. 2167

TMC_GetFullMeas) if distance measurements are made.

- Use meaningful command parameters. The waittime for instance must not be 0 but should be 1000ms or higher.
- Use a connection with a high data rate (e.g. USB or RS232 with baud rate 115 200 or higher).
- Use RS232 to USB converters only if necessary. Their their performance has to be tested before used for monitoring applications.

Nevertheless, the limitation of the reduced ATR resolution of 0.3mgon in dynamic tracking remains. As was shown in one of the field experiments, this low resolution may not be sufficient to identify vibrations with low amplitudes.

As demonstrated in the third approach the ATR sensor resolution limitation can be overcome by using the on-axis camera of an image assisted total station as the measurement sensor. The angular resolution of the on-axis camera of the MS50 or MS60 is about 5 times better than the angular resolution of the ATR sensor. We successfully performed the monitoring of vibrations of a footbridge using the on-axis camera of a MS50 and tracked the position of artificial and natural targets in the recorded video streams. The limitation when using a MS50 is that the video stream can only be recorded with 10Hz on an external computer. However, with the newer MS60 total station video streams with frequencies of 20Hz or even higher can be recorded.

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