

WFD – Wave Form Digitizer Technology White Paper

EDM

Technology



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Optimized Measuring Meets Individual Demands – the WFD Technology

Abstract

Combining precise total station capabilities, digital imaging, 3D laser scanning and GNSS compatibility in one instrument is a challenge successfully realized by the Leica Nova MS50 MultiStation (Grimm and Zogg, 2013). To achieve this level of integration and keep the well-known appearance and usability of a total station requires a seamless fusion of the latest technologies.

The Wave Form Digitizer (WFD) represents a new dimension in fast and accurate electro-optical distance measurements. It is critical to the successful merging of laser scanning technology and total station functionality in one instrument.

This white paper describes the technological background of the WFD principle and explains how an optimized balance of accuracy, speed and range is achieved. In this white paper the focus is on TPS (Terrestrial Positioning System) instruments which denote total stations and MultiStations. Benefits of the WFD technology as used by the onboard applications are highlighted so that the reader gains an insight into the WFD's advantages.

Introduction

Together with the launch of Leica Nova, a new measurement method found its way into the repertoire of Leica Geosystems' TPS technologies – the WFD electro-optical distance measurement (EDM) system.

Combining the characteristics of fast distance measurements, high accuracy and long ranges, the WFD contributes to the idea of mergeTEC – the fusion of the latest measurement technologies including (see Figure 1):

- Outstanding total station functionality
- GNSS connectivity
- High resolution digital imaging
- 3D laser scanning

This allows an operator in the field to choose the most suitable measuring technique to fulfil the individual demands while still using a single, well-known measuring instrument morphology.

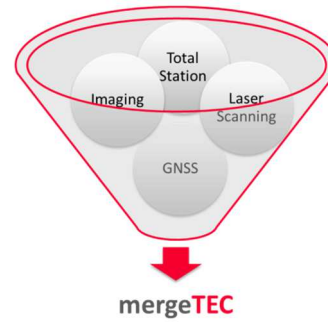


Figure 1 mergeTEC – combining technologies

Overview of Leica's EDM Technologies

Leica Geosystems provides distance measurement systems which show an ideal balance between measurement accuracy, speed and range.

All of Leica Geosystems' current TPS EDM methods have one thing in common – a visible laser beam transmitted by a laser diode, which is coaxial to the optical axis. The reflected light is detected by a sensitive photosensor and converted into an electrical signal. By analyzing this signal using one of the different methods, the distance to the object is determined.

The basic measurement principle of the different EDM methods is explained below.

Time-Of-Flight

The time-of-flight method calculates the distance based on the time a light pulse needs from the instrument to the object and back to the instrument (see Figure 2).

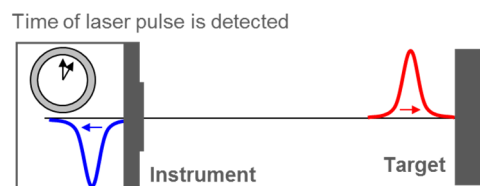


Figure 2 Schematic illustration of the time-of-flight EDM method

Once a light pulse is emitted, a timer starts and the EDM's photosensor is activated and waiting to measure incoming light. If a detected light pulse exceeds a specific threshold, then this pulse will be recognized as a reflected signal from the target and the time information will be used for the distance calculation.

Leica Geosystems does not use the pure time-of-flight technology in TPS instruments due to its rather large laser spot and lower measurement accuracy.

Phase-Shift

The distance calculation of this method is based on the phase-shift between the emitted and reflected signal and the number of full wavelengths (see Figure 3).

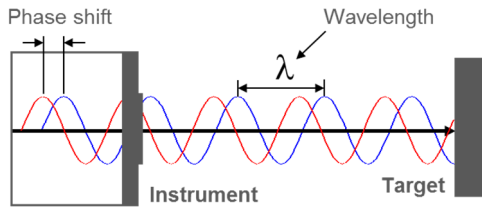


Figure 3 Schematic illustration of the phase-shift EDM method

The phase-shift measurement itself is only unambiguous within one wavelength (λ) of the signal. Therefore the number of full wavelengths has to be determined to achieve an absolute distance measurement.

To allow long distance measurements without prisms or reflective tapes, Leica Geosystems' System Analyzer is used (Bayoud, 2006). The method allows the evaluation of the total signal information, such as the entire signal shape and the channel amplification, for a more sensitive distance determination. This leads to an increase of the measurement range onto any surface.

In combination with an anamorphic lens to re-shape and optimize the laser beam and its small footprint highest accuracies in electro-optical distance measurements are possible. Such an anamorphic lens is built in Leica's current highest-end total stations which use phase-shift measurement systems, such as the Leica TS30/TM30 (Zogg et al., 2009) and Leica Nova TS50/TM50.

WFD - Wave Form Digitizer

The WFD combines the time-of-flight and phase-shift measurement technology where the distance is calculated based on the time between a start and a stop pulse which is digitized out of the received signal (see Figure 4).

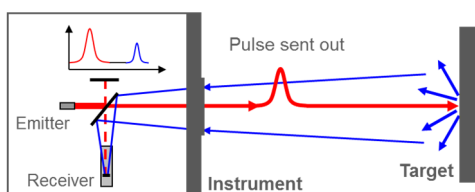


Figure 4 Schematic illustration of the WFD EDM method

The WFD system constantly evaluates, digitizes and accumulates the waveform of all reflected signals to precisely recognize and extract the start and stop pulses (see Figure 5).

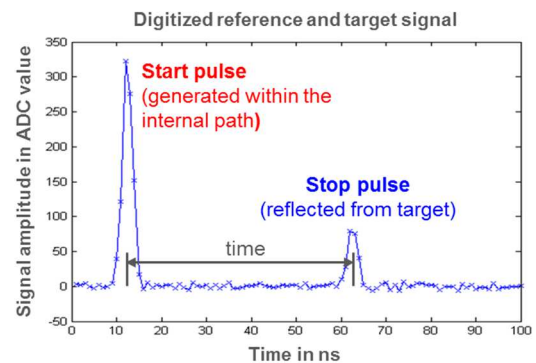


Figure 5 Start and stop pulses from accumulated measurements

Compared to a pure time-of-flight measurement system, the WFD technology results in a better overall measurement performance considering its fast distance measurements, small laser spot size, higher measurement accuracy and the long ranges.

These characteristics make the system ideal for use in the Leica Nova MS50 MultiStation. It is currently the only TPS instrument from Leica Geosystems on the market that utilizes the WFD technology.

Table 1 Comparison of the different EDM technologies regarding TPS instruments

Technology	Description
Time-Of-Flight	<ul style="list-style-type: none"> fast measurement time larger laser spot size lower measurement accuracy no (single shot) measurements if signal to noise ratio is too low
Phase-Shift	<ul style="list-style-type: none"> longer measurement time small laser spot highest measurement accuracy of all technologies
WFD	<ul style="list-style-type: none"> fast measurement time small laser spot size similar to phase-shift high measurement accuracy long ranges configurable

Understanding the WFD Technology

The WFD is a kind of time-of-flight measurement system but combines advantages of the phase-shift and the time-of-flight method into one single system.

The WFD's ability to deliver fast measurement times, high accuracy and long ranges is critical to the integration of 3D laser scanning in the Leica Nova MS50 – the world's first MultiStation.

The configurable EDM allows fast 3D laser scans of objects with up to 1'000 points per second, precise single measurements to prisms in a distance up to 10'000 m and precise single measurements to any surface in a distance up to 2'000 m using the same sensor.

Measuring Principle

A distance measurement with a WFD is not a single shot. When performing a distance measurement, short pulses with a frequency of up to 2 MHz will be sent out by the EDM sensor. A small portion of each pulse is directed through an internal channel inside the telescope. This pulse fragment is called start pulse. The major portion of the pulse will leave the telescope's optics and reflect on the target. The reflected signal is detected by the photosensor inside the telescope. This is known as the stop pulse. Both start and stop pulses are digitized as full waveform and accumulated from multiple signals. The time difference between accumulated start and stop pulse can then be used to calculate the distance as it is done in the standard time-of-flight method. The analysis and distance calculations are all performed directly in the telescope of the MultiStation.

To achieve a fast and precise distance measurement, multiple signals are digitized and accumulated directly in the telescope.

The more pulses that are sent out and received, the better the signal-to-noise ratio (SNR) becomes, the better the start/stop pulses can be digitized and the more accurate the distance measurement can be determined (see Figure 6). The SNR increases with the square root of the measurement time. Therefore a measurement time of for example 9 seconds leads to a SNR about three times better than for a measurement time of 1 second.

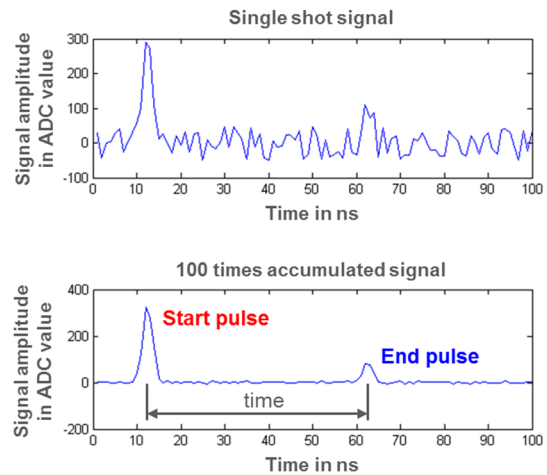


Figure 6 Single shot signal (above) and 100 times accumulated signal (below)

Not only the number of accumulated signals influences the quality of the distance measurement. Also the characteristics of the emitted pulses themselves represent an important contribution. Three features can be distinguished (see Figure 7):

- Output power (signal amplitude)
- Pulse width (T_{On})
- Repetition rate (T_{Rep})

The ratio between pulse width and repetition rate describes the so-called **duty cycle** of the emitted signal.

$$duty\ cycle = \frac{T_{On}}{T_{Rep}}$$

Assuming a fixed output power, a better sensitivity can be achieved by the use of a lower repetition rate. On the other hand, a smaller pulse width leads to a more precise determination of the pulse's barycenter and therefore to a higher measuring accuracy. Combining these two aspects means that a low duty cycle increases both the measurement accuracy and also the measurement speed.

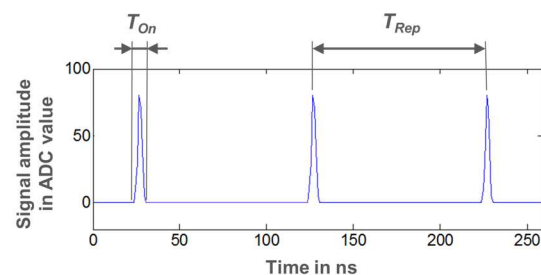


Figure 7 Characteristics of the emitted signal, including the pulse width (T_{On}) and repetition rate (T_{Rep})

Similar to the phase-shift method, the ambiguity of the detected signal has to be solved if a single frequency repetition rate is used. This is achieved by the application of varying repetition rates during the performance of each distance measurement.

Table 2 Parameters of the MS50 WFD

	Value / Range
Peak output	1 W
Carrier wave	658 nm
Minimum pulse width	1 ns
Repetition rate	100 KHz – 2 MHz
Sampling rate	500 MS/s

The WFD measurement method is not a rigid system. A major advantage of the WFD is the flexible configurability of both the duty cycle and the number of accumulations which affects the measurement time and range. It is therefore extremely versatile, since for individual demands the system parameters are optimized in a best possible way. Depending on the field of application and its requirements, the WFD either focuses on achieving highest accuracy, maximum speed, longest range or a combination of the three.

To fulfill individual needs in the field, the WFD is configurable from the highest accuracy over maximum speed to longest range.

For monitoring purposes for instance, accuracy and long range are crucial. In other applications, such as short range scanning, the range coverage can be reduced to allow maximum speed with an appropriate accuracy.

Optimized Measurements onto Prisms and Any Surface

Different reflectivity properties of retro-reflective prisms and diffuse scattering target points on any surface demand optimized measurement modes for both types of targets to ensure accurate and reliable distance measurements.

Because of the diffuse reflectivity, measurements onto any surface require a higher laser performance and a different shape of the laser beam to still accurately achieve a long range.

Table 3 Differences of the two main single measure modes for prisms and any surface

	Prism	Any Surface
Laser class	1	3R
Laser shape	slightly divergent	collimated
Repetition rate	500 KHz – 1 MHz	1 – 2 MHz
Maximum range ¹	> 10'000 m	> 2'000 m

The WFD detects start and stop pulses from the same emitted signal, which enables a minimum measurement time of 1.5 s for a single distance measurement in the standard measure mode. EDM measure mode "Fast" for prisms reduces the typical measurement time to 1.0 s.

Short-range measurements lead to a situation where start and stop pulses are very close to each other and therefore difficult to separate. In this special case, the WFD automatically adds a subsequent start pulse measurement while the outgoing stop pulse channel is closed. This procedure slightly increases the measurement time, however simultaneously ensures a reliable and accurate distance measurement. Evidence for this procedure is the closure of the outgoing channel, which is realized through a mechanical rotation of a revolver wheel (see Figure 8).

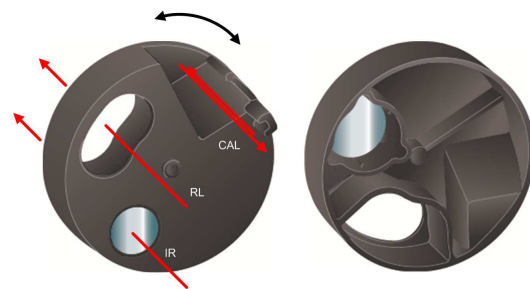


Figure 8 Revolver wheel, front and back view

The 'clack' sound of the rotating wheel can also be heard during internal calibration measurements, such as before each scan and continuous measurement. The short-range definition is < 12 m for prisms and < 6 m for any surface measurements.

¹ Overcast, no haze, visibility about 40 km, no heat shimmer

The minimum measurement time for standard measurements onto prisms is 1.5 s and increases with growing distance (see Figure 9).

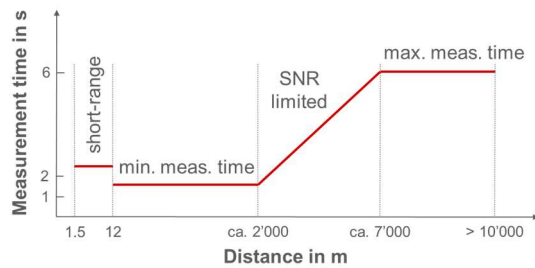


Figure 9 Approximate measurement time for measurements onto prisms (standard measure mode)

Targets on any surface also require a minimum measurement time of 1.5 s increasing non-linearly with growing distance due to the stronger influence of the varying target reflectivity and atmospheric conditions (see Figure 10).

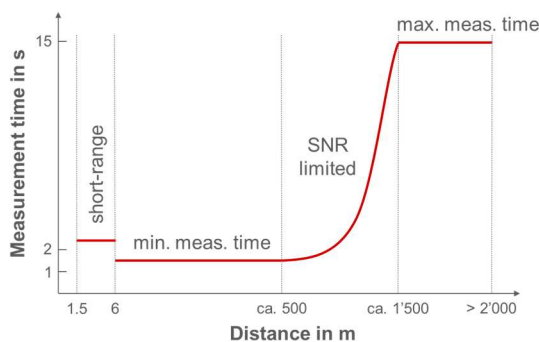


Figure 10 Approximate measurement time for measurements onto any surface²

Performance and Accuracy

Representing a measurement method with the advantages of both the time-of-flight and phase-shift methods, the Leica Nova MS50 with the WFD EDM achieves single distance accuracies of 1 mm + 1.5 ppm onto prisms and 2 mm + 2 ppm onto any surface according to ISO 17123-4.

Similar to the phase-shift characteristics, the WFD sensor provides a very small laser spot size of 16 x 25 mm at a distance of 100 m (Leica Geosystems AG, 2014). Known as Leica Geosystems' PinPoint technology it currently represents one of the smallest laser spot sizes in the TPS market.

² >500 m: measurement time strongly depends on the target reflectivity and atmospheric conditions.

Table 4 EDM accuracy

	Specification
Distance measurement accuracy onto GPR1 prism ³ (according to ISO-17123-4)	1 mm + 1.5 ppm
Distance measurement accuracy onto any surface ⁴ (according to ISO-17123-4)	2 mm + 2 ppm
Laser spot size at 100 m (width x height)	16 x 25 mm

Both the small laser spot size and an exact, coaxial alignment of the sensor with respect to the optical line of sight contribute to precise and reliable distance measurements even if the target point is on a tilted surface or close to an edge, such as a wall's corner.

The larger the laser spot size the larger the area around the aimed target point which will influence the distance measurement. Especially for measurements onto any surface a small spot size is essential for:

- less disturbing influences from the surrounding area around the target point, for example in the case of an irregular surface
- more reliable measurements close to an edge
- a better measurement performance on tilted surfaces

Following application test focuses on the reliability of distance measurements onto any surface with respect to the angle of incidence. First the instrument is measuring to the center point of a plane target plate which is orthogonal to the instrument's line of sight. Afterwards the target plate is rotated around its center point such that the (horizontal) angle of incidence changes without changing the distance to the instrument (see Figure 11).

³ Overcast, no haze, visibility about 40 km, no heat shimmer

⁴ Object in shade, sky overcast, Kodak Gray Card (90 % reflective)

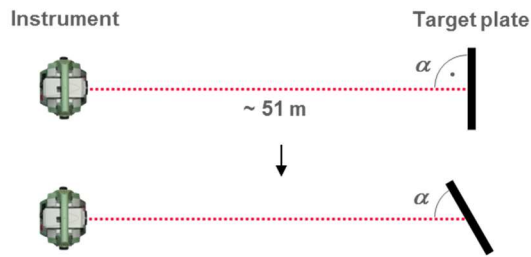


Figure 11 Schematic illustration of test measurements on a tilted surface (top view)

Extreme angles of incident (where α is smaller than 45° or bigger than 135°) decrease the quality of the distance measurement. Nevertheless the distance measurements in Figure 12 only vary few mm from the distance measurement orthogonal to the surface.

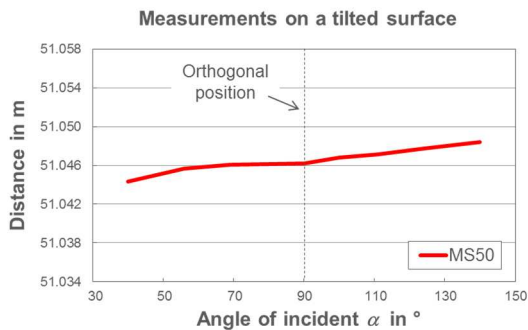


Figure 12 Distance measurements with respect to the angle of incident on a plane surface

Other investigations to the effect of the laser spot size can be done by test measurements on an edge. By placing a small box in front of a wall and repeatedly measuring the distance to this box and continuously aiming closer to the edge (and beyond), possible distance deviations at the edge can be determined (see Figure 13).

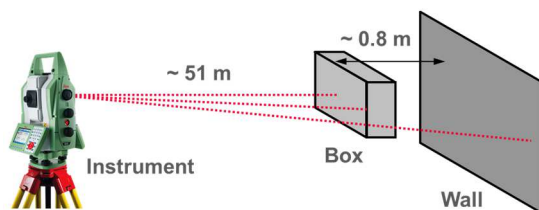


Figure 13 Schematic illustration of test measurements to an edge

A small laser spot size projects a small footprint on the target to be measured and therefore allows accurate distance measurements even close to edges.

The red points in Figure 14 mark the single point measurements and illustrate that the edges of the box were well resolved and no mixed dis-

tances between the wall and the box were measured. For the shown test, the aiming interval near the edges was 40 cc which corresponds to a point spacing of about 3 mm.

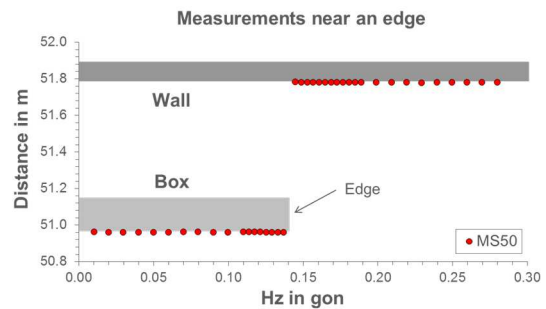


Figure 14 No mixed distance measurements near the edge of the box

Note that by projecting the full laser beam only on the target of interest, the highest possible precision of the distance measurements can be ensured.

The WFD's ability to configure its main focus, such as the speed, allows 3D laser scans of objects with up to 1'000 points per second. Furthermore different scan modes enable the operator to achieve best results with respect to the needs in accuracy, range and time. Within the scanning application of the MS50, four scan modes are available:

- 1'000 Hz: Standard mode up to 300 m
- 250 Hz: Optimized mode for performance & accuracy up to 400 m
- 62 Hz: Optimized mode for range & accuracy up to 500 m
- >1 Hz: Long range mode up to 1'000 m

By choosing between these four scan modes, different requirements regarding accuracy and range can be fulfilled in different applications.

The precision of 3D laser scans can be described using the term "range noise". The range noise is the standard deviation of the scan points' residuals to a modelled surface. The plane surface target is oriented perpendicular to the instrument's line of sight. A modelled plane is then calculated to best fit the measured point cloud. Investigations of scanning a standardized white and plane surface (90 % reflective) in different ranges and by the use of different scan modes result in a varying point cloud quality (see Figure 15).

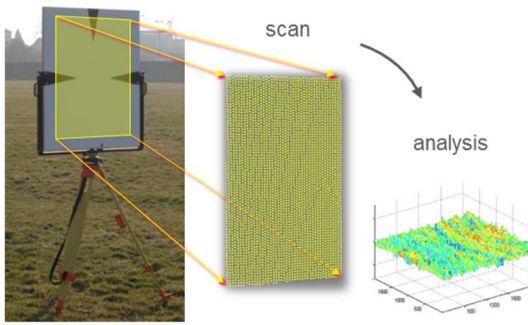


Figure 15 Determination of the range noise on a white, plane surface (90 % reflective)

The lower the scan rate, the more single shot accumulations can be performed for each point of the 3D laser scan. Hence the range noise decreases with a reduced scan rate (see Figure 16).

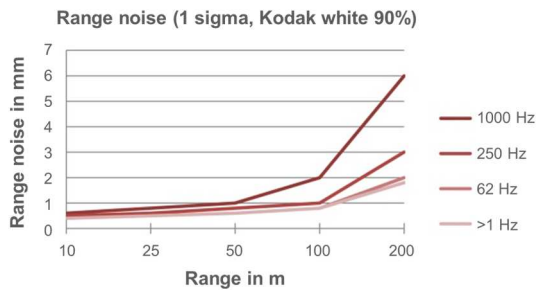


Figure 16 Range noise (1 σ) of the different scan modes in relation to the scan range

The absolute position accuracy of a measured point cloud is similar to a single measurement onto any surface and represents 2 mm + 2 ppm measured according to ISO 17123-4 (see Table 4).

Considering the single point and scanning performance, the WFD combines the advantages of enhanced total station functionality and the ability of performing highly accurate scans with a maximum measurement frequency of up to 1'000 points per second.

The WFD enables both highly accurate single point measurements and scanning capability within one measurement system.

Applications

The configurable measurement performance of the WFD in combination with other functionalities such as digital imaging and the fast motorization based on Piezo-technology (Zogg et al., 2009) assists the MS50 in covering a wide variety of surveying, engineering and monitoring applications with one instrument.

Prism Lock and Tracking

Automation tasks, such as precisely tracking a moving target, require both highly sensitive and fast sensors and actuators and the expertise of accurately evaluating the gathered data. By providing these attributes, the Leica Nova MS50 can properly measure and react on kinematic changes of the target of interest.

A major advantage of the WFD is the fast measurement performance. The faster a single distance measurement can be achieved, the more repeated measurements can be done in a given period of time. Therefore the trajectory of a moving target can be determined in a more reliable way resulting in a more accurate representation of the true course of motion.

In contrast to the phase-shift method, the WFD measurement method does not need to perform internal calibration measurements on a regular basis since the waveform of the detected signal is continuously analyzed. A single calibration measurement at the start of the tracking procedure is sufficient to ensure accurate measurements during the whole tracking process. This increases the number of evaluable distance measurements during a given period of time.

Figure 17 illustrates the higher number of successful distance measurements from the Leica Nova MS50 (with a WFD EDM) in comparison with the Leica Nova TS50 (with a phase-shift EDM) in which a static target in a distance of about 102 m was locked and continuously measured for a period of 1 min⁵.

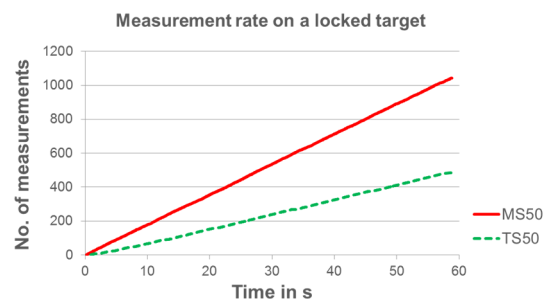


Figure 17 Number of successful distance measurements over time for MS50 (WFD EDM) and TS50 (phase-shift EDM)

⁵ Leica round prism measured in Continuous+ measure mode, controlled and read out via GeoCom connection (USB port)

Scanning

The intuitive and efficient workflow of the Leica Nova MS50 scanning application means that anyone with experience using a total station can acquire 3D point cloud data easily. No previous 3D laser scanning know-how is required by the operator.

The operator can precisely define the scan area in the live video stream of the onboard overview camera. This easy, yet accurate definition saves scanning unwanted objects and therefore time (see Figure 18).



Figure 18 Polygonal scan area definition using the onboard live video stream

In a wizard-based workflow the operator defines the scan resolution, the scan mode (speed) and an optional distance filter. A distance filter automatically rejects measured points which are outside a defined range, e.g. on unwanted objects behind the area of interest.

The 3D point clouds are directly stored in the same coordinate system as it is defined in the standard TPS station setup. In combination with the onboard 3D viewer the operator can therefore verify the data regarding completeness in the field. Missing point clouds can be discovered and measured. Furthermore 3D point clouds can be processed directly onboard for applications such as volume calculation.

The automatic registration of 3D point clouds on the MS50 allows an immediate completeness check directly in the field.

Several post-processing programs support data from the Leica Nova MS50. Each has a different focus on the individual needs of the user. Leica Infinity – the new office software from Leica Geosystems – supports the processing of various data sets collected by the Leica Nova MS50 in-

cluding single points measurements, 3D point clouds and images.

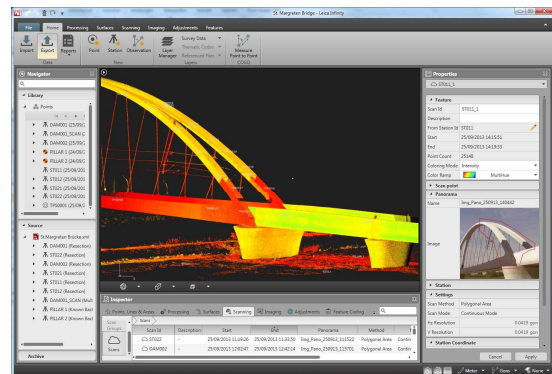


Figure 19 Visualization of the 3D point cloud by its intensity values in Leica Infinity

In the example of Figure 19 it can be seen, that the intensity map provides further information about the reflectivity of the scanned object. Lower parts of the bridge arches (shown in red) represent a different material, as can be verified in the image in Figure 18.

If a panoramic image of the scan area was taken, the true color information of the oriented digital image will be assigned to each individual point directly onboard the instrument. The 3D point clouds can therefore not only be visualized by the signal intensity but also based on the RGB values providing an additional aspect for a better understanding of the data (see Figure 20).

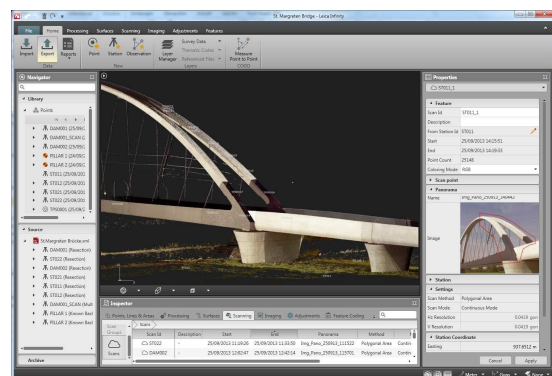


Figure 20 True color visualization for a better understanding of the 3D point cloud

Monitoring

Leica GeoMoS – the professional deformation monitoring software from Leica Geosystems – combines geodetic, geotechnical and meteorological data sets to match the needs of individual monitoring projects. Furthermore it is compatible with measurements from the Leica Nova MS50.

Repeated single point measurements and 3D laser scans can be performed and analyzed over short or long periods of time or even permanently to detect minimal structural deformations. The Leica Nova MS50 enables the user to integrate 3D laser scanning and single point measurements for permanent monitoring applications in one instrument.

The onboard cameras of the MultiStation can be used to easily define the area of interest to be measured. This can be performed remotely from the operator's office PC using Leica GeoMoS. Within this software the automated and periodic measured 3D laser scans are processed autonomously by the new n.Vec Technology (Wöllner, 2014). The results are provided as easy to read color maps so that, for instance, Structural Health Monitoring (SHM) can be performed. This enables the operator to recognize and react on laminar deformations of objects.

Concluding Summary

The WFD electro-optical distance measurement technology stands for a key element within mergeTEC and enables both precise 3D laser scanning and extensive and accurate total station capabilities in one instrument.

Outstanding Technology

Combining the time-of-flight and phase-shift technology, the WFD includes the advantages of both EDM methods by analyzing the full waveform of the received signals. Within one distance measurement, short pulses with a frequency of up to 2 MHz will be sent out to the target, reflected, received, digitized and accumulated so that a precise determination of the distance is possible.

Fast, Accurate and Long Range

Embedded in the Leica Nova MS50, the WFD achieves single distance accuracies of 1 mm + 1.5 ppm and reaches ranges up to 10'000 m for prisms. Measurements to any surface can be performed up to a range of 2'000 m. Moreover the WFD's ability to place the emphasis on speed enables 3D laser scans of objects with up to 1'000 points per second.

Enhanced Field of Applications

Depending on the application and its individual demands, the flexibility of the WFD allows the operator to either focus on achieving highest accuracy, maximum speed, longest range or a combination of these three aspects.

The combination of the WFD's measuring performance with features such as digital imaging and fast and precise motorization delivers outstanding automation, 3D laser scanning and monitoring functionality.

Representing a key element of mergeTEC, the WFD technology conquers today's challenges in surveying and enables the user to make the right the decision.

References

- Bayoud, F. A. (2006). Leica's Pinpoint EDM Technology with Modified Signal Processing and Novel Optomechanical Features. In *Shaping the Change, XXIII FIG Congress*, Munich, Germany.
- Grimm, D. E. and Zogg, H.-M. (2013). Leica Nova MS50. White Paper, Leica Geosystems AG, Heinrich-Wild-Strasse CH-9435 Heerbrugg.
- Leica Geosystems AG (2014). *Leica MS50/TS50/TM50 User Manual*. Version 2.0. Heinrich-Wild-Strasse CH-9435 Heerbrugg.
- Wöllner, J. (2014). Automatische Oberflächendeformationsanalyse im Geomonitoring. In Sroka, A., editor, *Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Bergakademie Freiberg*, volume 1 of *15. Geokinematischer Tag des Institutes für Markscheidewesen und Geodäsie. Am 15. und 16. Mai 2014 in Freiberg*.
- Zogg, H.-M., Lienhart, W., and Nindl, D. (2009). Leica TS30. White Paper, Leica Geosystems AG, Heinrich-Wild-Strasse CH-9435 Heerbrugg.

Whether measuring objects on a construction site, or monitoring a dam or a bridge; whether capturing an accident scene with digital imaging or scanning a building façade – you need reliable and precise data. The Leica Nova solution perfectly integrates all these capabilities in one compact solution.

Leica Nova embodies 90 years of innovative thinking to develop outstanding technologies. A solution that gives you the benefits of not only being able to take faster, smarter decisions, but also better and more informed decisions regardless of the application. Leica Nova represents our commitment to precision, reliability and flexibility. Faster, Better, Smarter, Simpler are the key words that describe the benefits of the Leica Nova; a unique solution that covers the complete process from capturing and visualising data, to deciding and delivering.

Leica Nova is the new dimension in measuring technology – make the right decision.

When it has to be right.



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**Distance meter (Prism),
ATR and PowerSearch:**
Laser class 1 in accordance
with IEC 60825-1 resp. EN
60825-1

Laser plummet:
Laser class 2 in accordance
with IEC 60825-1 resp. EN
60825-1

**Distance meter (Non-
Prism):**
Laser class 3R in
accordance with IEC 60825-
1 resp. EN 60825-1



Leica Nova MS50
Product brochure

Leica Nova TS50
Product brochure

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