Leica’s Pinpoint EDM Technology with Modified Signal Processing and Novel Optomechanical Features

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SUMMARY

With innovation, precision and reliability being the main targets of Leica Geosystems AG Total Stations, modernisations have recently focused on the software and hardware components of the PinPoint Electronic Distance Measurement (EDM) technology. Aiming at further improving the laser beam light distribution and its stability along with minimising the power consumption, a new optomechanical concept was developed that allows the combination of a reflectorless and reflector based EDM using a single laser beam emitter. This new hardware is supported by Leica’s unique System Analyser signal processing toolbox that permits an efficient assessment of the reflecting signals to achieve the accuracy, precision and reliability that mark Leica’s Total Stations. These two features are a part of other modifications that will identify the future of Leica’s EDM. In this paper, the presentation of these new developments is laid out and field tests are analysed.

ZUSAMMENFASSUNG

Tachymeter der Firma Leica Geosystems AG zeichnen sich durch Innovation, Präzision und Zuverlässigkeit aus. Aktuelle Entwicklungen konzentrieren sich auf Hardware und Software Komponenten der *PinPoint* EDM Technologie mit dem Ziel diese weiter zu verbessern. Ein neuartiges optomechanisches Konzept erlaubt die Kombination von EDM Messungen zu Reflektoren und reflektorloser Messung in einem einzigen Modul unter Verwendung einer einzigen Laserquelle, sowie die Verbesserung der Laserspot Charakteristik und Laserstrahl Stabilität. Diese neue Hardware wird unterstützt durch Leica’s einzigartige *System Analyser* Signalverarbeitung, welche eine effiziente Auswertung des reflektierten Signals in bezug auf Genauigkeit, Präzision und Zuverlässigkeit ermöglicht. Diese beiden Merkmale sind Teil der geplanten Verbesserungen für zukünftige Leica EDM Module. In diesem Paper wird ein Überblick über diese neuen Entwicklungen gegeben und einige Messergebnisse präsentiert.

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1. INTRODUCTION

Being the first to introduce the reflectorless (RL type) EDM for the surveying community, Leica has been systematically advancing its distance measuring technology to further extend the range and accuracy. In the current state, Leica's RL EDM can measure to distances over 500 metres to Kodak white with accuracies in the range of 3 mm and a maximum measurement time of 12 sec. As for the reflector measurements, ranges can reach up to 7500 m; in the Infra-Red (IR) type, ranges of 3000 m can be routinely measured with accuracies of around 6 mm and a typical measurement time of 1.5 sec; the Long Range (LO type) can measure up to 7500 m with accuracies in the range of 15 mm and a typical measurement time of 2.5 sec. The latest EDM version incorporated in TPS1200 can even measure to ranges of more than 9000m in IR type with a standard deviation of around 3mm. Table 1 gives information on the different ranges supported by the EDM and their respective accuracies with average atmospheric conditions.

Table 1: Ranges supported by Leica's EDM and their respective accuracies (according to ISO 17123-4)

EDM Type		Range (m)	Accuracy	Typ. Meas. Time (sec)
IR	Round Prism	3000	2 mm + 2 ppm	1.5
RL	Kodak White	500	2 mm + 2 ppm	3 - 6
	Kodak Grey	300	5 mm + 2 ppm	
LO	Round Prism	7500	5 mm + 2 ppm	2.5

The EDM technology currently available in the market can be classified as being based on either a time-of-flight (TOF) or a phase shift measurement. Although the later is chiefly used due its superior accuracy, owing to the low optical power signals on reflectorless objects, measurements over distances of more than 300 m might become difficult to achieve. On the other hand, time-of-flight metre have an advantage over the phase metres with regard to the range since measurements over distances of 500 m to reflectorless targets are easily achievable; yet their low accuracy is a main disadvantage. The System Analyser combines the advantages of the phase and TOF measurements without having to deal with their disadvantages; this is because it is neither a pure TOF metre nor a pure phase shift metre. This technology will permit accurate reflectorless measurements to distances beyond 500 m

(on Kodak White) being achieved within seconds. Furthermore, dependencies on general atmospheric influences, such as, dust content or smoke, will be reduced.
In addition, multi-target recognition (and potential measurement) will be possible through the new method. The existing methods perform inadequately when multi-target realisation is needed. In phase metres, the phase of the received signal of the various target objects is superimposed in an inseparable manner so that no recognizable separation into the components of the individual target objects is possible by the phase difference method. Although multiple target capability in time-of-flight metres is possible in principle, the poor accuracy of distance measurement and complexity of the device are among the major disadvantages of this measuring principle.

The laser beam light shape and distribution and its coaxial stability are two important issues in defining an accurate EDM. Leica Geosystems AG has been developing a new optomechanical concept that features a single laser beam emitter that allows reflectorless and reflector based measurements. This development is supported by the unique System Analyser signal processing toolbox that permits an efficient assessment of the reflecting signals to achieve the accuracy, precision and reliability that mark Leica's Total Stations.

Although the aim of this paper is to discuss this EDM technology, a quick discussion will be made also on two of the main components that constitute Leica's telescope, namely: the Automatic Target Recognition (ATR) and Power Search (PS).

The paper will be organised as follows. The second section outlines Leica's Total Station and its two components: ATR and PS. The third section discusses the current EDM Technologies. The fourth section examines the system analyser. Section five describes the new optomechanical design concept. Some numeric results are presented as well. The last section concludes the report.

2. LEICA'S TOTAL STATIONS (TPS SYSTEMS) OVERVIEW

Leica's TPS line consists mainly of the following instruments: TPS400/700/800/1200/2000. These instruments are categorised according to their accuracies and functionality with the TPS1200 being the single TPS that integrates all functionality.

TPS1200 (Figure 1) is considered not only the most efficient and accurate Total Station in the market that combines advanced hardware and software components in a high level synergy, but also the only that fully integrates GPS seamlessly to deliver the most professional engineering solutions for surveyors. This high-end instrument combines: motorisation with maximum speed of 45^{o}/sec, remote controlling, Automatic Target Recognition, Power Search, Guiding Light, accurate angle (up to 1 arcsec) and distance (up to 2 mm + 2 ppm) measurements, alphanumeric keyboard, ¼ VGA touch screen display, RS232 and Bluetooth interfaces, optional internal memory storage, circular level of 6/2mm arcmin sensitivity, laser plummet, endless manual drives, 6-8 hr battery operating time, and operating at environment temperature between -20^{o} C to + 50^{o} C and 95% humidity; all is in a package of around 5 Kg.

Figure 1: Leica's TPS1200

2.1 Automatic Target Recognition (ATR)

Automatic Target Recognition is the sensor that recognises the prism and measures its position on a CCD (or CMOS) array. This pixel information is used then to either steer the motorisation of the telescope and/or measure the position of the prism with respect to it. A laser beam is transmitted coaxially with the telescope towards the prism that is in the field of view (FOV) and the reflected beam is then received by the built-in array. Theoretically, the position of the (reflected) spot should coincide with the centre of the CCD chip in order to measure the angular position; however, to minimise the time for measuring, this match is not necessarily needed and instead an angular offset is computed to correct for the horizontal and vertical angles (see Figure 2). This angular offset is computed through measuring the Hz and V pixels of the spot on the image chip (and with the knowledge of the focal length).

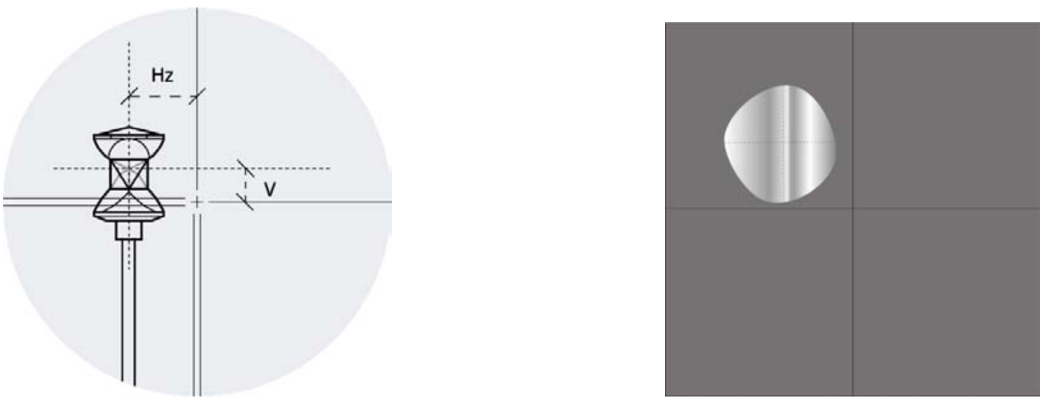

Figure 2: ATR's Hz and V offsets, and the prism's image on the CCD chip

In standard measuring mode, if the angular offsets exceed the limit of 50 cc (16``), they are instead used to control the motors in order to turn the instrument to approximately centre the crosshairs to the prism; the remaining offsets are used as angular corrections. This way, the Hz and V angles are measured to the prism-centre, even if the crosshairs are not aimed precisely at the centre of the prism.

If the prism is not located within the current telescope's FOV, an ATR search starts according to a pre-defined search window. If the prism is not found within this window, the ATR automatically expands the window until the prism is found. This happens in an iterative manner and the search window takes the form of a (growing) vertical rectangle.

2.2 Power Search (PS)

Depending on the specific application, the iterative solution of the ATR search might consume some time and the user has to instruct the ATR to retry the search every time the prism is not found. This potential drawback is overcome with the Power Search, which allows automatic prism detection within a short period of time.

The PS sensor consists of a transmitter and a receiver. When PS is activated, the transmitter emits a vertical laser swath while the instrument is rotating around its standing axis; when the laser swath detects a prism, the rotation of the instrument is stopped. The default search with PS consists of a short swing in anti-clockwise direction followed by a complete 360° turn in clockwise direction. (As in the case of the ATR, a PS search window can be activated and defined.) If a prism is detected the rotation is brought to a halt and an ATR search is performed.

The laser swath that is reflected back (Figure 3) can be the "image" of either a prism or a foreign reflecting surface; this "image" is a 3-D surface representing the strength and size of the reflected signal.

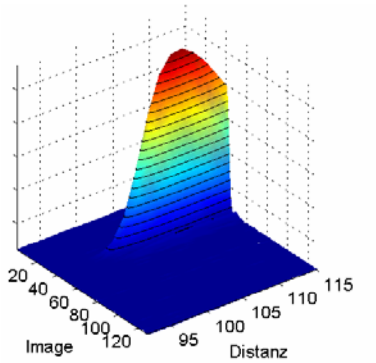

Figure 3: An image created by the PS laser swath

The detection, hence, of a prism and its differentiation from foreign reflecting surfaces is assessed through the knowledge of the reflected signal's strength and scanning duration (i.e., the size) of the received 3-D image relative to the distance according to a plausibility test. See Figures 4 for example; in case the reflecting object is a traffic sign, its signal signature and image size will fall outside the tolerance limits that are assigned for Leica's prisms.

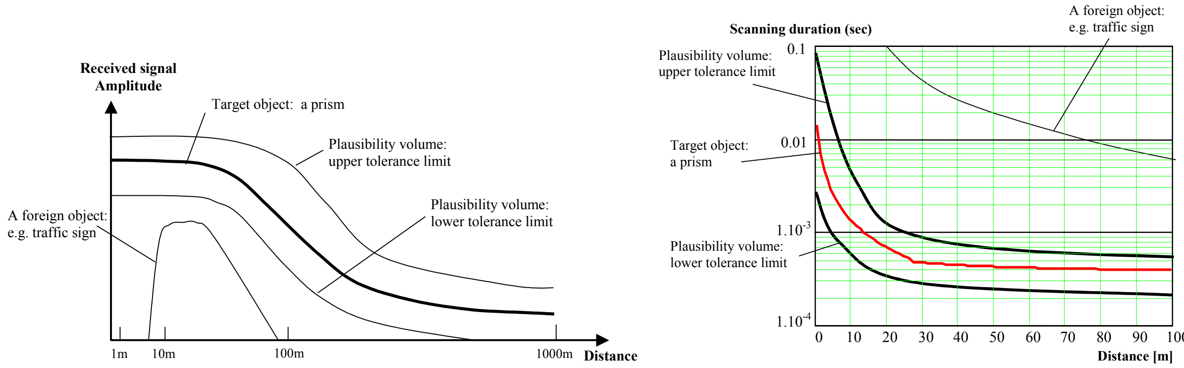

Figure 4: Schematic performance of the plausibility test

3. CURRENT ELECTRONIC DISTANCE MEASUREMENT TECHNOLOGY

As was mentioned previously, EDM technology can be classified into either a TOF or a phase shift measurement. Each of these methods has its advantages and disadvantages.

Figure 5 shows a diagram illustrating the principle of a TOF method. A transmitter 1 emits a light pulse 2, which is detected after reflection by the target, e.g. a retro-reflector 3, by the receiver 4. In general, transmitter 1 and receiver 4 are arranged in one unit.

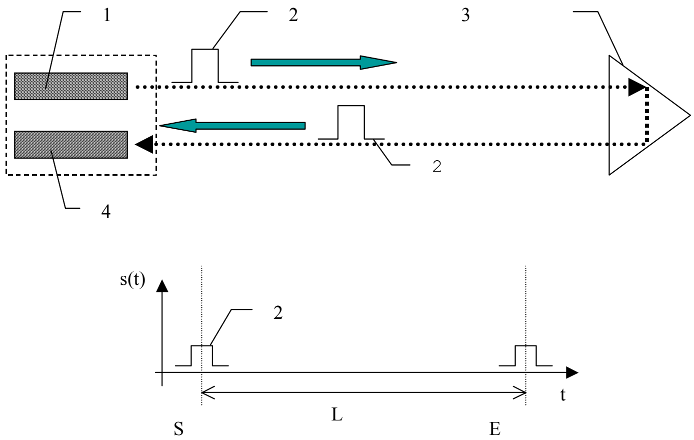

Figure 5: The principle of the transit time method

The distance is determined from L as being the time difference between the start time S of the emission of a light pulse 2 and the time E of reception. The determination of the time of reception is effected by the evaluation of a feature of the signal pulse s(t), for example by the exceeding of a signal threshold or by determination of the centre of gravity of the integrated pulse curve.

As mentioned before, the TOF devices permit distance measurements for long ranges, however the attained accuracy is too poor to match the surveyors' requirements. In addition, their poor performance or even failure in heavy rain or dusty air renders them ineffective in many situations. A further disadvantage of the TOF measurement is due to the laser source. Pulsed lasers having good beam quality, such as, for example, solid-state or microchip lasers are expensive and complicated with respect to control and power consumption. Semiconductor lasers are economical but, owing to reduced or lacking three-dimensional coherence, have been inadequate to date with regard to beam quality. There are to date no laser diode-based TOF metres that produce a laser beam with a small measuring spot. As a result, distances to edges cannot be accurately surveyed.

Figure 6 shows a diagram illustrating the principle of a phase measuring method, in which the distance between a unit and a target is determined. A transmitter 1' emits the modulated light signal as light wave 2' to a target which in turn may consist of a retro-reflector 3, and said light signal is reflected back from there to the receiver 4'.

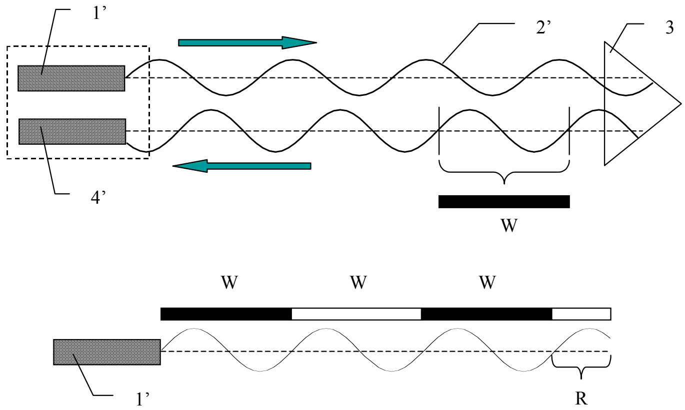

Figure 6: The principle of the phase measuring method

In contrast to the TOF method, no time difference between emission and reception of a signal pulse is registered in this case. The phase shift of the incoming and outgoing periodic signal is recorded. This shift is dependent on the distance between unit and target, since this distance corresponds to a multiple of the wavelength or pulse train interval W of the emitted light wave 2' and a residual R. This residual is the non-integral component remaining on division of the distance by the wavelength W. The measured phase shift is a measure of the residual R, so that, with knowledge of this residual R and the number of wavelengths W, the distance between measuring unit and target can be derived. Since the number of wavelengths W is not directly determined as an integral component in this method, an additional resolution of this ambiguity must be carried out. This can be affected, for example, by the use of a plurality of modulation frequencies (typically 2 to 5), for which the absolute phase of the received signal is calculated sequentially relative to the transmitted signal. The distance to the one target object can then be derived from the plurality of these measurements. The disadvantages of this method are briefly outlined in the Introduction.

4. LEICA'S PINPOINT ELECTRONIC DISTANCE MEASUREMENT TECHNOLOGY

Considering the disadvantages of the existing distance measurement methods, it has been the objective of the "System Analyser" to:

- Permit accurate (in the mm range) RL measurements to objects over large distances (> 500 m) within few seconds (< 12 sec).
- Permit identification (and correct surveying) of multiple targets.
- Permit distance measurements independently of general atmospheric influences, such as, dust, smoke, mist, rain or snowfall, etc.
- Make on-board distance calibration available which runs simultaneously with the distance measurement to avoid thermal drifts and interrupts of measurement flow.

To achieve these objectives, a specific choice of the modulation frequencies is carried out differently from the traditional phase measurements. They are changed or selected in a specific manner owing to the flexible and rapidly switch-able direct digital frequency synthesiser and they may be changeable as a function of the number of target objects and their distances. Preferably, only high modulation frequencies in the MHz to GHz range are emitted so that the system becomes selective with regard to TOF to hard targets and blind with regard to soft targets, such as rain, mist or snowfall. A further advantage of the use of high frequencies is the resultant increased accuracy of distance measurement. In the case of exclusively high frequencies, each frequency contributes to the final result of the parameter determination. This is not the case with conventional phase metres.

However, according to the well-known relationship between sensitivity and measurement speed, if the number of frequencies increases the "System Analyser" will be more sensitive but slower.

A fundamental element of the "System Analyser" is the evaluation of the total signal information to determine the distance. It is not only the phases as in the phase difference method or the transit times as in the time-of-flight method that is evaluated. The total signal information contains the entire signal shape in the time or frequency domain, channel amplification and attenuations, noise, etc.; thus they are all measured and included in the evaluation by the "System Analyser".

Since the method has principally the capacity of multiple target capabilities, it would therefore be capable of simultaneous calibration over an internal reference light path, which can be the first target object, and the distances of all further target objects surveyed relative to the known reference object are thus free of temperature drifts and further dispersive influences.

4.1 Signal Modelling

The signal model of the "System Analyser" is based on a time-invariant linear input-output system, whose behaviour is described by a pulse-response $h(t)$. (Time-invariant system is valid only when considering that the prisms and/or EDM are stable during the entire measurement time.) The signal behaviour of a linear electronic system can be described by the impulse response function $h(t)$, or its frequency response $H(\omega)$ that can be calculated by the Fourier Transformation (FT) of $h(t)$. When knowing $h(t)$ then the distance can be calculated similar to the time of flight method, therefore a solution would be to determine $h(t)$. For a linear EDM system, $H(\omega)$ is defined as:

$$\mathrm{FFT}: h(t) \rightarrow H(\omega) = \frac{Y(\omega)}{S(\omega)} = \frac{\mathrm{FFT}: y(t) \rightarrow Y(\omega)}{\mathrm{FFT}: s(t) \rightarrow S(\omega)} \qquad (1)$$

The system-descriptive transmission function is the quotient of the respective Fourier transformed received and excitation signals. The complex frequency response of the system analyser has the following form:

$$H(\omega) = \frac{a_n \cdot (i \cdot \omega)^n + a_{n-1} \cdot (i \cdot \omega)^{n-1} + \cdots + a_0 \cdot (i \cdot \omega)^0}{b_m \cdot (i \cdot \omega)^m + b_{m-1} \cdot (i \cdot \omega)^{m-1} + \cdots + b_0 \cdot (i \cdot \omega)^0} \cdot \left(\sum_{k=1}^{d} \rho_k \cdot e^{-i \cdot \omega \cdot t_k} \right) \qquad (2)$$

Where $\omega = 2\pi f$ is the angle of frequency f, i is the imaginary unit, d is the number of target objects, ρ_k is the reflectivity of target k and t_k is the signal transit time proportional to the distance. The distances are calculated according to (c is the velocity of light):

$$D_k = \frac{c}{2 \cdot t_k} \qquad (3)$$

The first term of equation (2) describes the so-called dispersive influences, produced by the electronic components, such as laser diode, receiver diode and filter and they result in amplitude and phase changes from the input to the output of the system. The second term consists of a sum of exponential functions and describes the sought transit times between the total station and the individual target objects.

In order to permit a measurement of the transit times with high accuracy, the first term must either be eliminated computationally or measured and eliminated by means of a system calibration. The later is achieved by determining $H(\omega)$ using the above-mentioned internal reference light path. For the system calibration, equation (2) can be written completely in a polar or exponential representation:

$$H(\omega) = |H(\omega)| \cdot \exp(-i \cdot \omega \cdot t_{disp}(\omega)) \cdot \left(\sum_{k=1}^{d} \rho_k \cdot e^{-i \cdot \omega \cdot t_k} \right) \tag{4}$$

By means of the system calibration, the system amplification $|H(\omega)|$ and the dispersion $t_{disp}(\omega)$ are determined at the frequencies emitted in the measuring signal and thus be assumed known in the actual distance measurement to the target objects.

Following the system calibration, the calibrated response function for the one-target case is:

$$H_C(\omega) = \rho_1 \cdot e^{-i \cdot \omega \cdot t_1} \tag{5}$$

And for the multi-target case with d targets is:

$$H_C(\omega) = \sum_{k=1}^{d} \rho_k \cdot e^{-i \cdot \omega \cdot t_k} \tag{6}$$

This is the theoretical base of an EDM-system irrelevant if it is a pulsed or a continuous wave (CW) apparatus as long as it behaves linearly including external targets at locations with time of flight times t_1 (or t_k). It has been shown that the term $H(\omega)$ is not the most efficient way to analyse the system, therefore Leica has chosen to use a merit-function in coincidence with the maximum likelihood principle that contains range parameters to determine the time t_1 (or t_k) that it takes the laser beam to travel double the distance between the EDM and target.

Accordingly, the practical solution takes an adapted maximum likelihood approach, by which the phase and amplitude of all received modulated signals are evaluated in an advanced mathematical formulation that considers all the modulation frequencies as being combined in a single merit-function. An example of the outcome of this advanced mathematical formulation combined with an associated frequency set is the “time signals” of Figure 7, where the first reflects a distance of a single target at around 100 metres, and the second reflects the distances of two targets at around 50 m and 110 metres.

Leica’s system analyser uses a pulsed modulation scheme where the received signals are sampled and stored in a buffer. Successively a merit-function is being built up based on using all the incoming signal information. Thus, the distance calculation is done by evaluating the numerically constructed time signal.

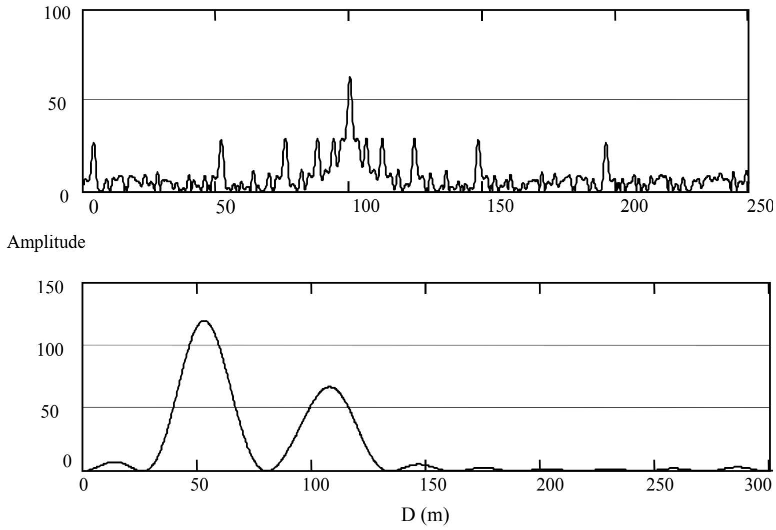

Figure 7: The output of the System Analyser for a distance of 100 m

Some of the key properties of this new measurement principle are summarized as follows:

1. No low but only high frequencies of at least 100MHz are generated in order to collect distance information with exclusively high resolution. In this way, every frequency contributes to the final result giving high accuracy. Thus, the measurement time gets shorter and sub-mm distance resolution is achievable. No time is wasted for ambiguity resolution.

2. Ultra short laser pulses in sub-nsec range within pulse-trains of ≥ 100MHz. This way, much of the energy is emitted at higher harmonics up to 1000MHz again supporting high distance resolution.

3. The receiver unit collects the higher harmonics up to 500MHz (BW).

4. The number of used modulation frequencies depends on the strength of the received signal:
   - At high signal levels 4 frequencies are sufficient to measure with the specified precision
   - At low signal levels up to 10 frequencies are emitted and analysed.

5. After sampling the received signals, a merit-function is calculated which is comparative to a time-of-flight signal. The time-of-flight signal has its maximum at the distance to be estimated.

6. Further advantages of the new measurement principle are its high sensitivity and its inherent ambiguity resolution. To determine the number of waves or pulses in air is not anymore a problem.

4.2 Comparison with other Manufacturers

Leica's EDM was compared with three other distance metres from three different manufacturers, of which two employ the TOF method and the third is a phase shift metre. The four sensors were put on an interferometer baseline of a length of 60 meters and a reflectorless distance measurement was done at every 0.35 m.

Figure 8 depicts the results of the comparison of each EDM relative to the distances measured by the interferometer. It was noticed that the other three systems had an offset of between 4 and 12 mm. At the first glance, this could be referred to an un-modelled offset between the interferometer and the systems; however, the fact the one of the three EDM's has an average offset of 6 mm and the other two have their offset of around 11 mm makes the un-modelled offset seem not realistic. Since no explanation could be really made, it was decided that these offsets be removed. Looking at the solid lines, it can be seen that Leica's System Analyser EDM outperforms the other three EDM with a factor of two.

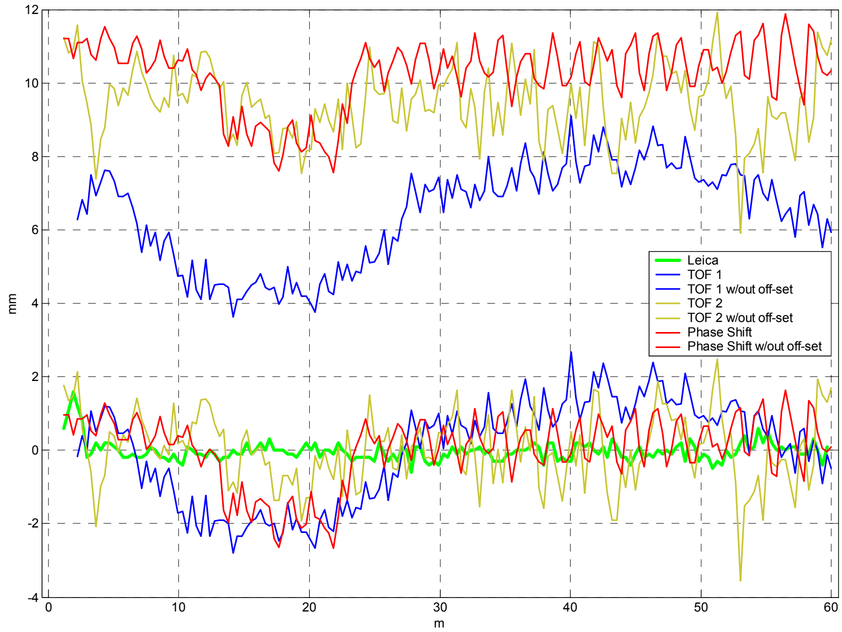

Figure 8: Differences between and the interferometer and the four EDM sensors

5. OPTOMECHANICAL FEATURES

Every part of a total station has to be designed in way to be an integral part of the whole system. No doubt that the telescope design, which embraces the actual telescope optics, the EDM and other sensors, has a vast impact on the reliability and quality of any total station. Aiming at further improving its telescope, Leica has decided to employ a single laser diode for both, reflectorless and reflector measurements (Figure 9).

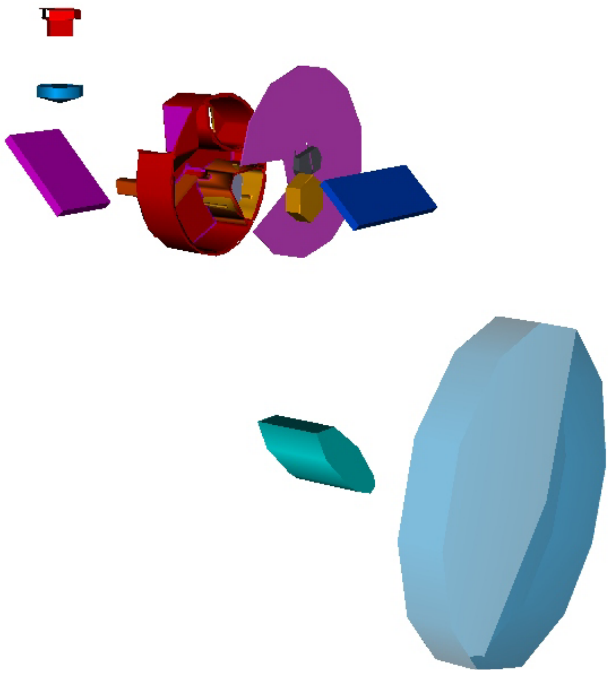

Figure 9: A proposed Optomechanical design

To achieve this, a revolver wheel (no. 4 in Fig 9) is built into the beam path that can take 3 positions:

1. CAL position: the wheel rotates to first fix end position where the beam hits a prism and gets deflected for internal calibration purposes

2. Reflector position: the wheel rotates to second fix end position where the beam penetrates a negative lens that widens the beam to suit for prism measurement. In this case, the laser beam also passes through a circular filter wheel (no. 5 in Figure 9) that intelligently takes a position that depends on the strength of the reflected laser.

3. Reflector-less position: the wheel rotates to a middle position where the beam gets through a hole without being thwarted. The beam also passes through the filter wheel.

Through this design, a number of advantages can be stated:

- Improved optical beam path due to the reduced number of parts in the optical path.

- Improved stability due to the lack of moving mirrors/lenses (where old designs forced the laser beam to be mirrored by means of a moving mirror) and improvements of the geometric coupling.

These advantages will:

- Improve the MTF (Modulation Transfer Function): sharper optical picture/impression for optical sighting through telescope.

- Eliminate the need for user adjustment of the laser beam

- Allow no misalignments or deviations between the reflector and reflectorless beam.

Because of the proposed optomechanical concept and a new laser diode, the laser spot will have better geometrical characteristics in terms of small size, round shape, optimal light distribution, more visibility, etc. These characteristics improve the quality of the distance measurements and make it more reliable and fit for corner and small edges measurements. Figure 10 shows the size and shape of Leica's EDM laser spot at distances of 5, 35, and 55 metres. Figure 11 shows an example of corner measurements carried out by Leica TPS1200 compared with another total station by a different manufacturer.

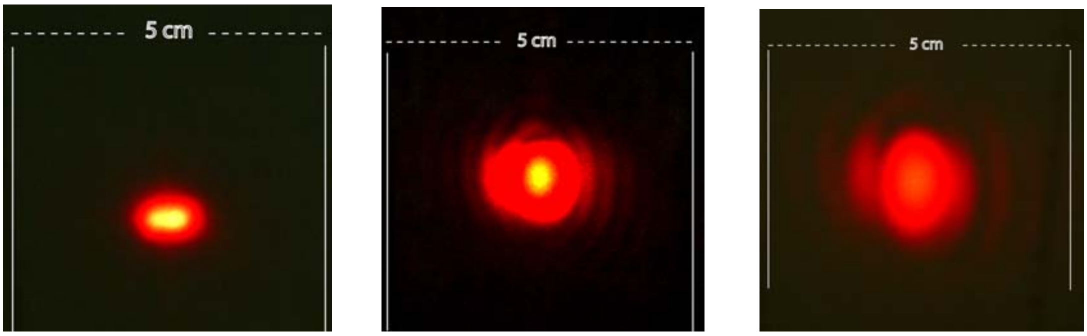

Figure 10: Leica's laser spot size at distance: 5, 35, and 55 m

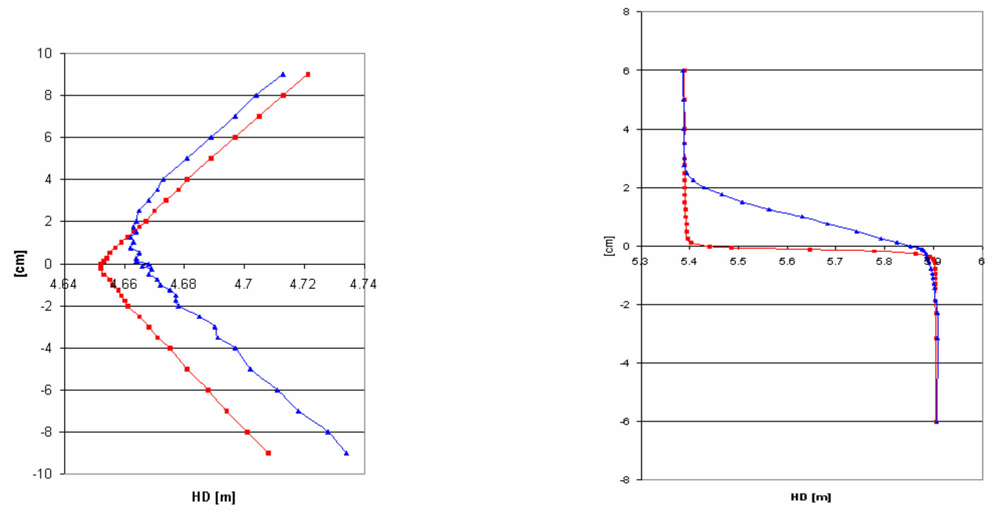

Figure 11: Corner measurements using Leica's EDM compared with a time-of-flight EDM

6. CONCLUSIONS

The paper discusses Leica's EDM system Analyser. The method was analysed and compared with the TOF and phase shift methods and it was found that its performance surpasses these existing methods.

The system analyser is able to measure accurate distances with 4 to 6 times lower signals than with a conventional phase-method. Onto a Kodak Gray (with reflectivity 18%) the range is more than 400m, whereas traditional phase meters reach 100m only. Onto white targets more than 750m are easily achievable. Further investigations are carried out to improve the maximum likelihood approach model in order to measure ranges to more than 1000m on bright diffusive targets.

The paper features, as well, a proposed optomechanical design that overcomes potential disadvantages found in the old design, especially in terms of beam stability, image quality, laser beam spot geometry, etc.

Through its continuous aim towards excellence, Leica Geosystems AG constantly and systematically seeks and builds innovation to deliver high quality solutions for the geomatics industry.

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