Direct Reflex EDM Technology for the Surveyor and Civil Engineer

R. Höglund & P. Large

*Trimble Integrated Surveying Group,
Westminster, Colorado, USA*

Trimble

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The latest technology to revolutionize the surveying industry is direct reflex measurement, electromagnetic distance measurement without cooperative targets or prisms. Direct reflex (DR) enables surveyors to accurately measure remote points without first locating a physical target at each point. Direct reflex therefore opens new possibilities for one-person surveying, increased productivity, and improved personal safety. When direct reflex combines with robotic technology, the possibilities for one-person surveying increase even further.

DR is achieved using either of two EDM technology methods: Time of Flight (Pulsed Laser) *or* Phase Shift*. Because the DR Standard technology of the Trimble 3300, 3600 and 5600 series uses the phase shift method, and the* DR200+ and DR300+ *of the Trimble 5600 use the Time of Flight method, Trimble is able to offer surveyors a choice between these technologies.*

Each measurement method is designed to suit particular types of needs and applications. The purpose of this paper is to define both methods and to outline the advantages and disadvantages of each, thereby enabling surveyors to choose which of these options—Time of Flight or Phase Shift—best suits their requirements.

DR Technologies: Time of Flight (Pulsed Laser) and Phase Shift

EDM measurement without a co-operative target can be achieved by either of two methods: *Time of Flight (Pulsed Laser)* or *Phase Shift*. Time of Flight employs a pulsed laser to provide the measurement principle behind DR200+ and DR300+ technology. Phase shift provides the principle behind DR Standard technology.

As illustrated in Figure 1, the optical principles for each method are different, each having its own advantages and disadvantages.

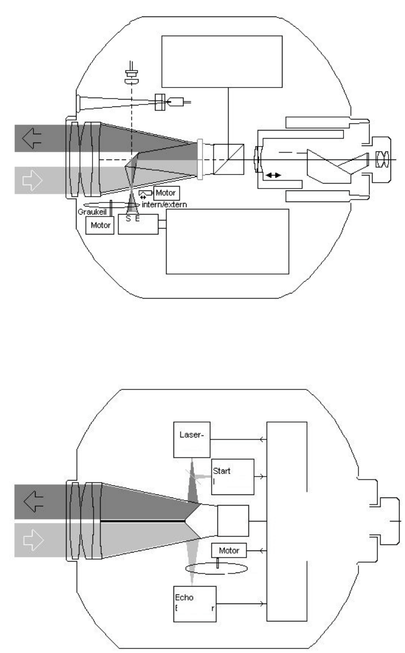

Figure 1: Optical Principles for Phase Shift (top) and Pulsed Laser (bottom) EDM

Phase Shift Measurement

The phase shift method works by modulating a measuring signal onto a continuous carrier wave signal. The method is similar in principle to the way music is modulated onto a carrier for radio broadcasts, except that for EDM the carrier is at light wavelengths.

The instrument measures a constant phase offset despite inevitable variations in the emitted and received signal. Only the phase offset is obtained through the phase comparison— initially, a cycle ambiguity prevents the total distance from being directly estimated. This cycle ambiguity is resolved using multiple measurement modulation wavelengths, which provides a unique integer number of cycles. Once the integer number is achieved, the distance to the target can be very accurately determined—up to ±(1 mm + 1 ppm) for DR Standard in Standard Measurement mode with prism; ±(3 mm + 2 ppm) without.

Time of Flight (Pulsed Laser) Measurement

The Time of Flight (TOF) method precisely measures timing information to calculate a range measurement.

In simple terms, the EDM generates many short infrared or laser light pulses, which are transmitted through the telescope to a target. These pulses reflect off the target and return to the instrument, where electronics determine the round trip time for each light pulse. As the velocity of light through the medium can be accurately estimated, the travel time can be used to compute the distance between instrument and target.

Note that although the TOF method typically has the longest range, it still meets the highest standards for eye safety, because the intervals between laser pulses prevent the accumulations of energy that can harm.

Each pulse is a direct range measurement, so if thousands of pulses are sent in a second while the measurement is being taken, a good average value can be achieved relatively quickly. Figure 2 illustrates a measurement distribution for the Trimble DR200+ pulsed laser DR. Typically 20,000 pulsed laser measurements are taken every second. This can be averaged to an accurate distance measurement value.

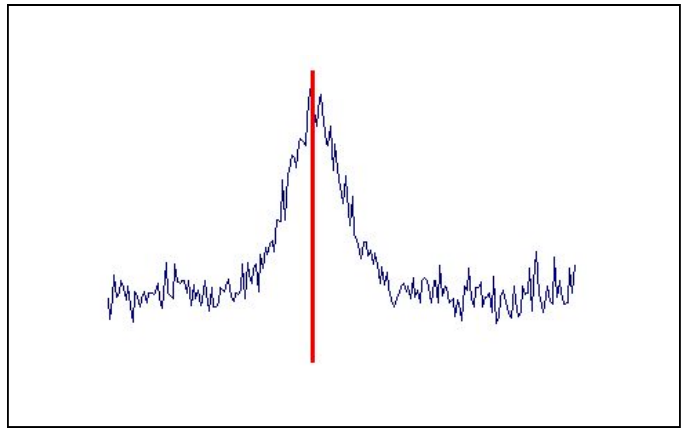

Figure 2: Averaging of TOF Pulses

Conventional pulsed laser implementations may degrade accuracy (up to 10 mm) when compared to phase shift EDM. However, the Trimble DR200+ and DR300+ use patented signal processing techniques to achieve both long range and high accuracy—±(3 mm + 3 ppm) for DR200+, with or without a prism. Note also that some conventional pulsed laser EDM instruments require the telescope to be focused before a range is taken—this is not necessary with the Trimble DR200+.

Comparison of the Two Techniques

In summary, the TOF method uses light pulses to directly measure distances, while the phase shift method uses modulated light to measure a phase shift, which provides distances once a cycle ambiguity is resolved.

The pulses used for the TOF method can be many times more powerful than the energy used for a phase shift EDM. The TOF method can therefore measure much longer distances (with or without a prism) than the phase shift technique.

The TOF method has traditionally been slightly less accurate than the phase shift method. However, with the modern Trimble patented signal processing methods described earlier, this difference has now become insignificant, being only the difference between ±(3 mm + 3 ppm) and ±(3 mm + 2 ppm) for the two methods when measuring to non-cooperative targets. (This makes a difference of just 0.1 mm even at 100 m.) For many practical purposes, the difference is insignificant, and the advantage of the much longer range achieved with the TOF method makes it highly desirable for many users.

The physics of light determines that all light beams diverge (spread out) as a function of distance from the emitter. See Figure 3 below. This is true for both TOF and phase shift EDM, although the size and shape of the beam divergence effect differs (spreading out of the beam from perfect collimation) resulting in a difference in the measuring spot. These different divergence effects have their own advantages and disadvantages, and these are discussed in more detail later in this paper.

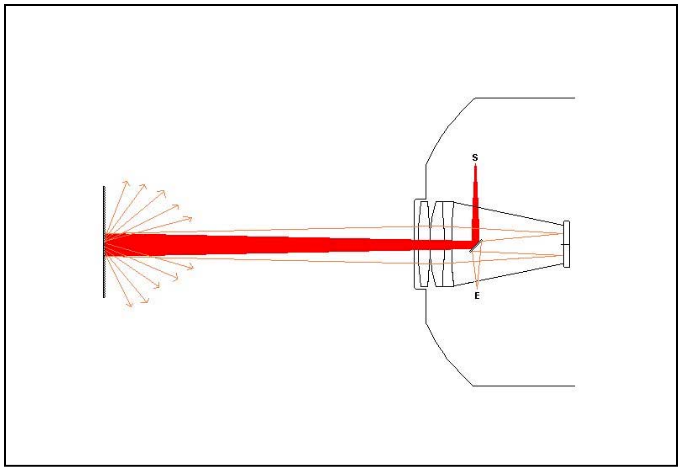

Figure 3: Beam Divergence Effect

The TOF and phase shift techniques also differ in their tolerance of interruptions to the line of sight during measurement, for example, interruptions such as traffic passing through a beam while surveyors are measuring near roads. Because the TOF method combines direct pulses with Trimble's signal-processing techniques, it is generally more tolerant of line-of-sight interruptions than the phase shift method. Interruptions during phase shift measurement may require cycle ambiguities to be reset.

DR Range Performance

Comparing the range performance of different EDM technologies is straightforward when using a cooperative target such as a standard surveying prism, as the measurement surface is always the same. When measuring to a single prism using Long Range mode, the ranges for the DR200+, DR300+ and the DR Standard options are basically the same, at 5500 m (18,000 ft) and 5000 m (16,400 ft) respectively. Not all phase shift EDMs can measure as far to a single prism as the DR Standard, so when comparing other implementations of the technology, check all specifications.

Kodak Grey and Kodak White Standards

When comparing range performance without a standard prism, the comparisons are not so straightforward. Because in practice DR measurements are made to many different kinds of surfaces, in order to make a fair comparison of range performance when not using a prism, measurements must be made to an appropriate standard surface, for example, the Kodak Neutral Test Card, (commonly called the Kodak Gray Card). See Figure 4.

Figure 4: The Kodak Neutral Test Card (Kodak Cat. No. E1527795)

The Kodak Gray Card has been a recognized standard in professional photography for many years. It is a card of usually 4" x 5" or 8" x 10", is about 1/8" thick, and is gray on one side and white on the other. The gray side, known as Kodak Gray, reflects *precisely 18%* of the white light that strikes it. The white side, Kodak White, reflects *precisely 90%* of the white light that strikes it. Because Kodak White is more reflective than Kodak Gray, it is important to compare measurements to either Kodak Gray *or* Kodak White, but not one with the other.

The survey industry contains some inconsistencies in its use of standard surfaces, and so it is very important to ensure that any comparisons made between products use measurements made to the same surface. For example, some specifications refer to just a “Kodak Card” without stating which side—18% or 90% reflective—was used for the test.

The correct names for the two sides of the Kodak Gray Card are “Kodak Gray Card 18% Reflective” and “Kodak Gray Card 90% Reflective”. The original choice of an 18% reflective target for the Kodak standard for photographs was based on the fact that most everyday scenes and objects to be photographed average at about 18% reflectivity of light. This is also the reason why most photographic exposure meters are calibrated to provide accurate exposure at 18% reflectivity. Usually the same is true for scenes and objects to be surveyed—18% reflection provides a good average value.

In field surveying practice, DR measurement is made to a variety of everyday objects, which are not usually 90% reflective. For this reason, the range to the 18% reflective Kodak Gray standard is the most reliable indicator of the range that will be achieved in day-to-day practice. The range to the 90% reflective Kodak White standard only shows the maximum range of the EDM to a *very* favorable highly reflective target.

Range Comparisons

Table 1 below compares the published maximum ranges of Trimble’s DR Standard, DR200+, and DR300+ when used to measure to different surfaces.

The table shows that for range the TOF method used in the DR200+ outperforms phase shift measurement by between four and eight times. The techniques used in the DR300+ achieve almost 10 times the range to a 90% surface compared to the phase shift result.

Table 1: Trimble DR Range to Various Target Surfaces

Surface	DR Standard	DR200+	DR300+
Kodak 90%	>70 m (230 ft)	>600 m (1968 ft)	>800 m (2,625 ft)
Kodak 18%	>50 m (164 ft)	>200 m (656 ft)	>300 m (984 ft)
Concrete	>50 m (164 ft)	>300 m (984 ft)	>400 m (1,312 ft)
Wood	>60 m (197 ft)	>300 m (984 ft)	>400 m (1,312 ft)
Light Rock	>50 m (164 ft)	>250 m (820 ft)	>300 m (984 ft)
Dark Rock	>40 m (131 ft)	>150 m (492 ft)	>200 m (656 ft)

Measuring to Wet and Non-Reflective Surfaces and to Oblique Angles

The higher energy levels of the TOF method also provide longer range when measuring to wet surfaces. When measuring to a wet surface, field tests usually show two or more times the range with the TOF method than with the phase shift method, especially at oblique angles of measurement. This is further extended with the DR300+ option.

The TOF method also improves the likelihood of successful measurement to non-reflecting and oblique surfaces, for example, to wet roads. In these situations, the ability to measure is the criterion. Additionally, the speed of measurement of the TOF method assists in measuring to points through busy traffic.

The TOF method also measures most successfully to narrow objects such as cables and overhead wires. Again, the criterion in these instances is simply to be able to measure.

Laser Safety Standards

Despite the higher energy levels of the TOF method, EDM instruments using this technique, such as the DR200+ and DR300+, generally meet the highest standards of laser safety and are classed accordingly. This is because the laser pulses used, although powerful enough to measure at ranges of hundreds of meters, are short in duration and therefore the laser beam does not accumulate energy. The continuous laser beams that are sometimes used to extend the range of phase shift EDM instruments, can lead to an accumulation of energy which may be hazardous.

The three laser classes relevant to most surveying instruments are Class 1, Class 2, and Class 3R.

Class 1 Lasers

Class 1 lasers like the Trimble DR200+ and DR300+ are invisible lasers that meet the highest safety standards: direct exposure of the measurement beam to skin or naked eye is unlikely to harm. Class 1 lasers also do not cause danger if another surveying instrument is pointed into the source of the Class 1 laser beam. The IEC standard 60825-1 states “Lasers that are safe under reasonably foreseeable conditions of operation, including the use of optical instruments for intrabeam viewing”.

Class 2 Lasers

Class 2 lasers emit visible laser radiation, which may be hazardous to the naked eye if the beam is stared directly into. Users must be especially careful to avoid looking directly into the beam with optical instruments such as binoculars or other surveying instruments.

Class 2 lasers are generally safe to use in public places (where most surveying is carried out) without any special precautions, other than not staring directly into the laser beam. Regulations do not require the use of warning signs, audible warnings, or specialist personnel training for lasers in this class.

The Trimble DR Standard falls into Class 2, as does the visible point laser option on the 5600 series. Many everyday handheld laser devices, such as pocket laser presentation pointers, also fit into Class 2.

Class 3R Lasers

It is possible to extend the range of a phase shift EDM by increasing the power of the light source—typically from less than 1 mW to more than 4 mW. However, the higher-powered continuous laser light emitted increases the health and safety risks of the laser beam, changing the classification of the laser to Class 3R.

The international IEC 60825-1 standard outlines additional precautions necessary for using Class 3R equipment. An excerpt is shown below:

USER SAFETY PRECAUTIONS CLASS 3R

Class 3R laser products used for surveying, alignment and leveling. Only qualified and trained persons should be assigned to install, adjust and operate the laser equipment. Area in which these lasers are used should be posted with an appropriate laser warning sign. Care should be exercised to prevent the unintentional reflection of radiation. Only Class 1 or Class 2 laser products should be used for demonstrations, displays and exhibitions. Training: Only persons that have received training to an appropriate level should be placed in control of such a system. The training should include: familiarization with the system operation proper use of hazard control procedures, warning signs, etc. the need for personal protection, accident reporting procedures bio effects of the laser upon the eye and the skin. Precautions should be taken that persons do not look directly into the beam. Precautions should be taken to ensure that the laser beam is not unintentionally directed at mirror-like surfaces Audible or visible warning required when laser is switched on.

Given these precautions, while using Class 3R equipment may be practical for areas such as mines and certain construction environments, it may not be so practical in open and public areas.

When examining product specifications, it is important to compare a comparable class of laser (Class 1 or 2) and to fully understand the regulations and obligations of the user for other laser classes such as 3R.

No Trimble surveying instruments fall into Class 3R.

Measurement Time

When comparing DR range, it is important to also compare measurement times, because the time it takes to measure affects productivity. At longer range, TOF methods are generally much faster than phase shift methods, as the latter typically have a measurement time that increases as a function of the distance being measured. Measurement times for phase shift DR EDMs are often quoted as a residual time for short ranges, plus an additional time for each increase beyond that range.

Taking the example of the DR Standard phase shift DR, the measurement time in tracking mode is 0.8 seconds for the first 30 m (99 ft) plus another second for every additional 10 m (33 ft). At 100 m, this becomes 7.8 seconds. The quoted measurement time for the TOF DR200+ or DR300+ is 0.4 seconds at all ranges. For higher accuracy measurements, both methods require more time. However, the TOF method does not increase as a function of range. This point is important as a faster measurement time on every distance has a very positive effect on productivity in the field.

Figure 5 shows typical measurement times as a function of range for the Trimble DR200+/DR300+, the Trimble DR Standard, and a non-Trimble phase shift DR.

The figure shows that the TOF pulsed laser method is typically four times faster than the pulsed laser at the maximum range of the phase shift instrument. Longer ranges cannot be compared as they are beyond the reach of the phase shift based DR EDMs.

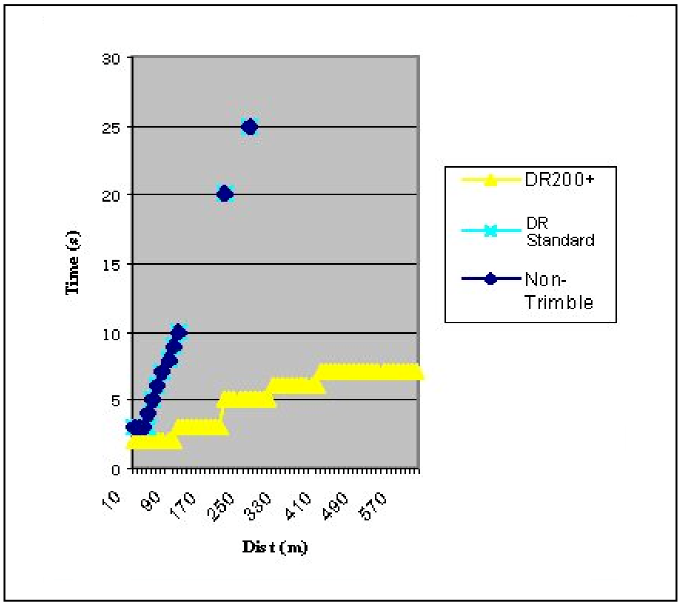

Figure 5: Measurement Time as a Function of Range

Beam Divergence and Accuracy

The beam of light used for measurement spreads out as it travels from the source, as was illustrated in Figure 3. The nature of the divergence is different for a TOF pulsed laser than for a continuous phase shift instrument: when the laser leaves the instrument, the diameter of the measurement beam for the pulsed laser is slightly larger than for the phase shift beam. As the pulsed laser typically travels two to three times farther than the phase shift EDM, the measuring spot may grow to about 4 cm in diameter at longer ranges. However, this does not mean that the measurement accuracy for either method is degraded to 4 cm, the accuracy remains as specified at ±(3 mm + 2 ppm) (DR Standard) and ±(3 mm + 3 ppm) (DR200+/DR300+). It simply means that the area sampled for measurement is of that size.

A larger or smaller measuring spot or "footprint" can have both advantages and disadvantages. A larger footprint at longer range is generally advantageous, as it enables smaller objects—particularly power lines and antennas—to be detected and measured. With a smaller footprint they might be missed. (Because the high-energy pulse can spread over a wider area, it is more likely to hit a narrow target, yet still measure very accurately).

The smaller footprint of the phase shift EDM has advantages when many tight corners and vertices are measured at very close range, such as in internal building surveys, or when measuring through keyholes. Although the error is reduced with a smaller beam size, it should be noted that an error is still present in these circumstances. The most accurate solution to measuring into tight corners is to eliminate the problem entirely by using simple on-board application programs, for example, those that allow the user to make angle and distance measurements to two points on an adjacent wall, and then to precisely measure the horizontal and vertical angle to the corner or vertex. See Figure 6. This method works just as well for both phase shift and TOF DR and enables a higher accuracy position for that point to be determined than can be achieved by direct measurement using any type of DR technology. (Because both TOF and phase shift EDMs have beam divergence, an error will exist for both whenever a direct measurement is taken to a corner or vertex).

Beam divergence also has an effect when measuring with any DR technology to surfaces at very oblique angles to the line of sight. It affects measurements using either method, but again can be significantly reduced using another simple on-board application, which allows a Face 1 and Face 2 measurement. The effect of the slope caused by the oblique angle can be eliminated using a canceling effect.

Field Tests

When evaluating DR technologies, surveyors can easily test the performance of the technologies and the validity of manufacturers' claims.

To test range, simply choose some remote objects or structures up to 600 m (~2000 ft) away, and see which can be measured to using the different DR options.

To simply test the effects of beam divergence and accuracy, take an object for which the true dimensions can be easily measured, such as a pencil. Hold the pencil against a wall at any range and measure to it. Then, take the pencil away and measure to the wall. Compare the difference between the two distances with the known difference, which is the width of the pencil. Using either type of DR technology, the difference will be seen, regardless of the beam size. Another test is to try to measure to overhead power lines and telephone cables at different ranges.

Test tolerance to beam interruptions by taking DR measurements to objects on the other side of a busy road, where traffic will pass through the beam.

Check accuracy to known points and be sure to compare typical measurement times at different distances: when surveying hundreds of points per day, measurement times significantly influence productivity.

Also test the applications supported on board the instrument, such as those described below.

DR Applications

While the measurement capabilities of the EDM are important, so are the capabilities of the field software. It is the field software that enables surveyors to make the best use of DR technology.

The Trimble 3300, 3600, and 5600 instruments support a number of useful applications, depending on the choice of control unit. Some are described below.

Measurement Range or Gate

Occasionally, surveyors need to measure using DR to a distant object when another object is so close to the line of sight that it may be measured instead. The solution is to do one of the following: measure to an object of the approximate same range as the desired object, or measure to the object that is not desired. Use one of these values to set a measurement range, for example, to only measure distances greater than 100 m, or only measure to objects between 120 m and 130 m.

For example, if the line of sight to the top of a water tower is crossed by some power lines whose measurements are not wanted, first measure to the power lines. If these are 45 m away, set the application to measure only distances greater than 50 m—then only the top of the water tower will be measured.

Standard Deviation Countdown

A desired standard deviation for the measurement can be set, for example, 0.010 m or 0.001 m. The software then measures until the desired precision is reached. If the desired precision is not reached in a predetermined maximum number of measurements, the achieved standard deviation is presented to the user with a choice of whether or not to accept the measurement.

Face 2 D-Bar Measurement

Measurements can be made in D-Bar (averaging mode) with both Face 1 and Face 2, after which the mean of the two distances is taken. This is useful when measuring with the DR200+ or DR300+ at very oblique line-of-sight angles.

Accurate Corner Measurement

All DR types, TOF and phase shift, will have an error when measuring to corners and vertices, because of the beam divergence effect, where the beam spreads out as it travels further from the source. When the beam is pointed directly at a corner, some of the measurement energy is reflected by the walls before the beam reaches the corner.

The corner measurement effect is shown in Figure 6, where the beam front for the phase shift DR gets closer to the corner than that of the TOF DR. (The source is located at the same distance away.) However, both methods experience some range error.

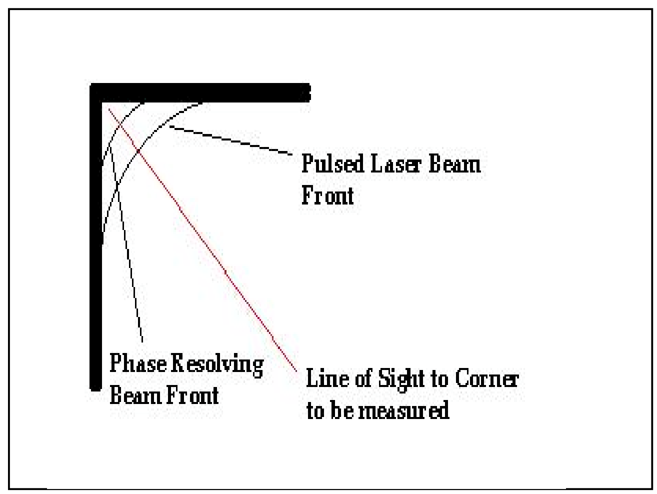

Figure 6: DR Corner Measurement Effect

Because of this error, by far the most accurate way to measure a corner is by a combination of angle and distance measurements. One application is to take two 3D DR measurements to one of the walls, which establishes a known line or plane surface. The angle to the actual corner to be measured can be measured very accurately and is not affected at all by the corner effect. This application allows the two wall measurements and the angle to the true corner to be measured in sequence, from which the accurate position of the true corner is automatically resolved. See Figure 7.

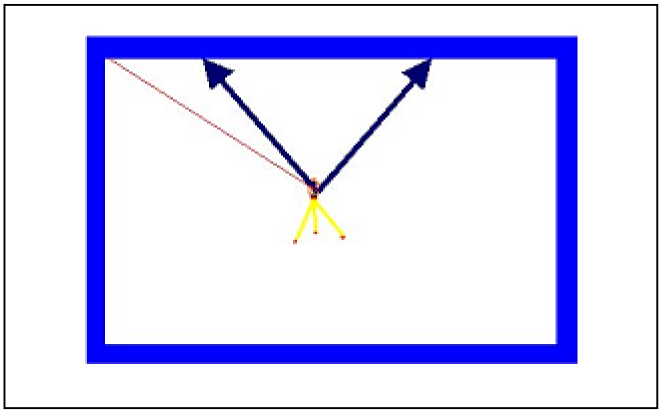

Figure 7: True Corner Angle Measurement Application

Two-line intersection measurement is similarly supported in another application available on the Trimble 5600.

Eccentric Point Measurement

This application is illustrated in Figure 8, which in this example is a circular water tower for which the position of the center is required. Clearly this cannot be measured directly, but it can easily be resolved using DR techniques and the supporting software, without having to send a target to the top of the tower.

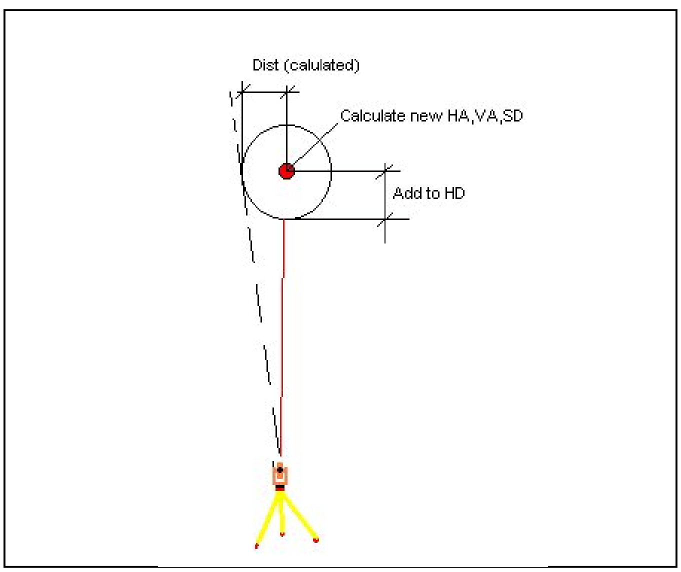

Figure 8: Eccentric Point Measurement

First, a DR measurement is taken to the center of the tower as viewed from the instrument location, which can be done from a location of up to 800 m (2,600 ft) away with the DR300+, 600 m (1,968 ft) away with the DR200+, or up to 80 m away with the DR Standard, depending on the surface type. Then the angle is measured from that line of sight to the edge of the tower as viewed from the instrument location. From this, the radius of the tower is automatically calculated, from which the position of the centroid is automatically resolved.

Surface Scanning

Surfaces such as mine walls, cliff faces, and spoil heaps can be automatically measured using the scanning mode, which takes automatic measurements at a user-defined interval within a predetermined window. Trimble office software such as the Terramodel® software can be used to build and visualize such a surface. See Figure 9.

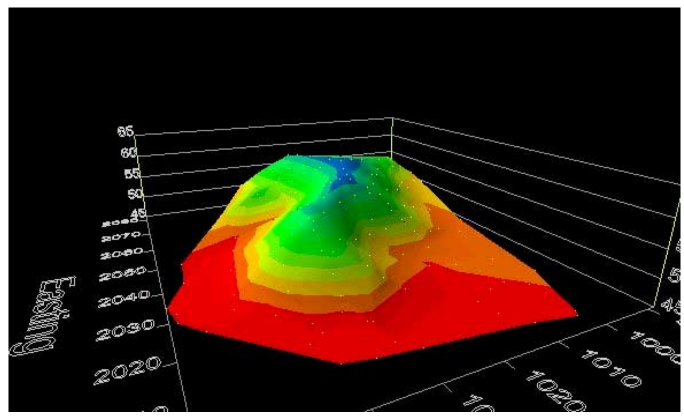

Figure 9: Visualization of Scanned Surface

Conclusions

Direct Reflex measurement offers significant productivity and safety advantages. Inaccessible points and areas can now be measured with ease. Hazardous locations such as cliffs, dams, rock faces, mine walls and live traffic areas can be measured without having to send a person into the danger area. Building facade surveys can be carried out very rapidly using this technology, and all with a one-person surveying crew, which considerably reduces cost. The ability to make this kind of non-contact measurement when engaged in road and rail surveys also reduces disruption to traffic and improves safety.

The two approaches to enabling this technology have been explained—the Phase Shift and Time Of Flight methods—along with the advantages and disadvantages of each. Typical support applications have also been described.

The phase shift technique used in the Trimble DR Standard technology is an entry level DR solution available in the 3300, 3600 and 5600 series total stations. The DR Standard also offers a co-axial laser pointer, which is particularly useful for applications in underground surveying and tunneling. It is also ideal for surveyors who spend most of their time conducting interior surveys, and so do not need the longer range capability of the DR200+ and DR300+. These are the applications for which the DR Standard option is recommended.

The Time of Flight, or pulsed laser method, as used in the DR200+ offers high accuracy in DR mode ±(3 mm + 3 ppm) and typically achieves two to three times or more the range of the phase shift DR. Therefore, the DR200+ is recommended as the most practical instrument for surveyors who spend most of their time working above ground and out-of-doors, and so benefit from the general longer range capability and the ability to measure further in wet conditions or to oblique angles.

The DR300+ has the longest range capabilities currently available to the surveyor, typically achieving up to six times the range of a phase shift DR without compromise in accuracy or measurement time. This premium option is recommended for exterior applications where far reaching direct reflex measurement in the 150 m–800 m (490–2600 ft) range is required to minimize instrument setups and increase productivity.

With the DR Standard capabilities of the 3300, 3600, and 5600, and the pulsed laser capabilities of the DR200+ and DR300+ in the Trimble 5600, Trimble offers surveyors the most complete range of reflectorless distance measurement solutions available anywhere. By understanding the differences between the phase shift technology used in the DR Standard and the Time Of Flight technology used in the DR 200+ and DR300+, surveyors can make an informed choice regarding the most suitable option for their particular range of applications and needs.

Technical Appendix

For more information, refer to the following:

3300 Data Sheet – 12415B (11/01)

3600 Data Sheet – 12414A (02/02)

5600 Data Sheet – 12412A (10/02)

Reference: IEC60825-1 / 2 Laser Eye Safety.

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Geomatics & Engineering Division
Trimble Navigation Limited
5475 Kellenburger Road
Dayton, OH 45424-1099
1-800-538-7800
+1-937-233-8921
+1-937-233-9441 Fax
http://www.trimble.com