White Paper

Inside the Trimble X7:
Deep Dive into Trimble X7 Auto-Calibration

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https://geospatial.trimble.com/products-and-solutions/laser-scanning-solutions

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Did you ever ask yourself how the auto-calibration works in the Trimble X7?

Maybe you heard a detailed technical explanation or a response as simple as, "automatically without targets or user interaction." In a nutshell, it's Trimble X-Drive technology that enables the Trimble X7 to automatically calibrate itself ensuring consistent data quality from scan to scan.

The purpose of this whitepaper is to explain the technology behind Trimble X7 Auto-Calibration and the many benefits it brings to 3D laser scanning. The following topics will be covered.

- Automatic Calibration
    - o Internal Collimator
    - o Automatic Angular Calibration
    - o Automatic Distance Calibration
    - o Smart Calibration
- Impact on Return on Investment
- Summary of the Features and Benefits

We faced the challenges of 3D scanning. And we solved them. Here's how.

Automatic Calibration

Let's start with a simple analogy before we get into the nuts and bolts. Consider the calibration equipment required to produce and service 3D laser scanners today. Different equipment can weigh over 200 kg (500 lbs) and cost over €200,000 ($220,000). Now imagine miniature versions of this equipment included inside the Trimble X7 to enable automatic calibrations anywhere. Part of the secret is in the base where a miniaturized internal collimator performs full angular calibrations and axis error measurements.

Figure 1: Miniaturized internal collimator is in the base

The Trimble X7 auto-calibrates distance and angular measurements similar to how calibration equipment is used to calibrate "standard" laser scanners, but on a much smaller scale. The EDM scanner and the deflection unit are integrated inside the scanning center unit. The deflection unit contains a high-speed motor and an encoder system. Located in the center unit is a mirror capable of measuring the trunnion axis error. In addition, a standard total station vertical drive and angle encoder system is integrated into the alidade, meaning that the complete center unit including the deflection unit and EDM source can be rotated around the trunnion axis in the manner characteristic of total stations.

Internal Collimator

For the first time in an optical instrument, the integration of an internal collimator inside the instrument base enables the calibration process to be totally automated. No targets or user interaction is required to measure the primary axis errors.
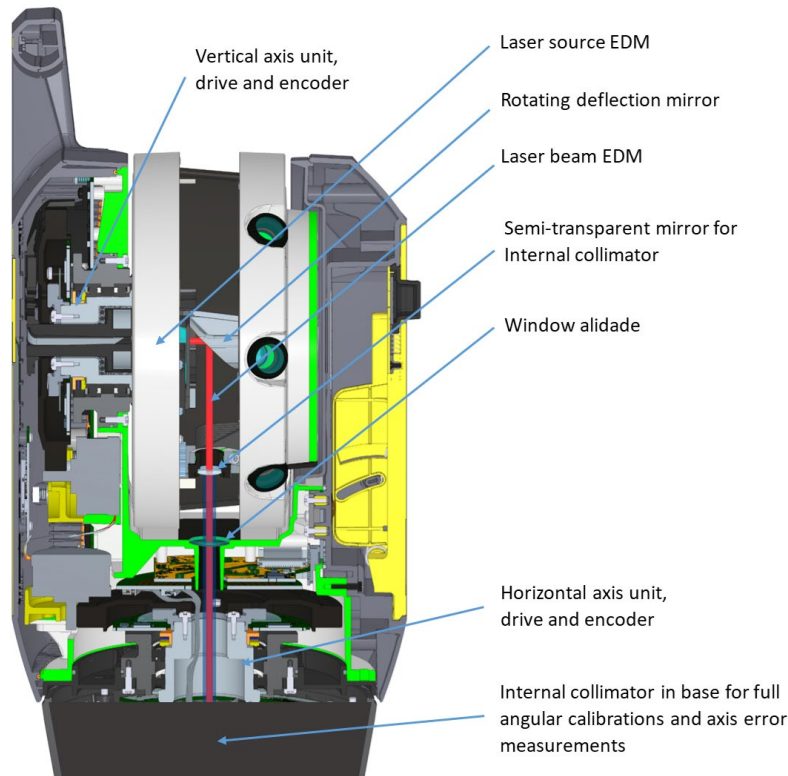

Vertical axis unit, drive and encoder

Laser source EDM

Rotating deflection mirror

Laser beam EDM

Semi-transparent mirror for Internal collimator

Window alidade

Horizontal axis unit, drive and encoder

Internal collimator in base for full angular calibrations and axis error measurements

Figure 2: Internal Collimator for Trimble X7

The laser beam emitted by the scanner head can be measured over a full radius using the internal collimator camera, while the alidade drive system turns the center unit to different positions. The process of measuring a singular line of sight horizontal and vertical collimation error from a total station is extended to include infinite line of sight measurements taken over a 360° dome. This is done using X-Drive's combination of two vertical drive systems, the one placed in the alidade and the deflection unit for scanning.

This auto-calibration procedure comes with multiple advantages. The first being that because the technology for the alidade's encoder system is adopted from total stations, the precision is already down to less than 3" (arc seconds) and provides confidence that the scanner head will be properly calibrated at each individual deflection unit encoder position for both horizontal and vertical collimation error. The procedure also accounts for all remaining alignment deviations inside the scanner as well as deflection unit encoder errors and rotational speed impacts. For example, in the case that the EDM beam and the deflection unit rotation axes are not identical, the scanning plane will not be perfect, but rather slightly bent.
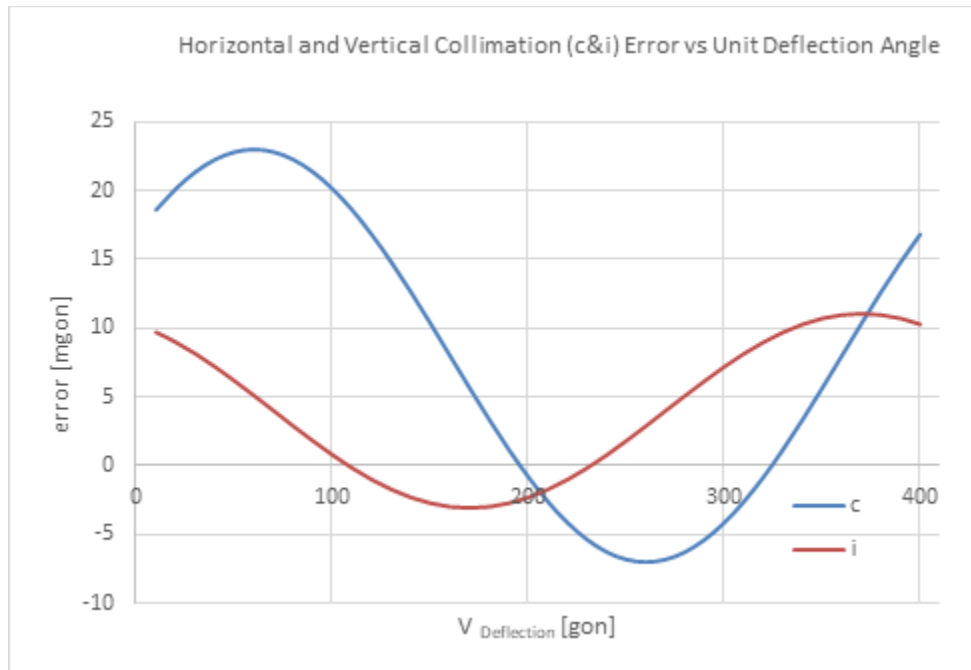
Figure 3: Typical Error Curves from Scanners

Figure 3 shows a diagram of this misalignment effect between the EDM laser and the rotation axis. Data following sine and cosine distributions is typical of this effect. The curve can be calibrated with the internal collimator and the vertical drive inside the alidade. In the field this self-calibration can be completed by taking a few spot measurements at different vertical angles, gathering enough data to create the characteristic spread to fall within the accuracy range.

## Automatic Angular Calibration

The angular calibration is done with the X-Drive dual vertical deflection system which calibrates the angular accuracy of the rotating mirror by using the servo system and the auto-collimator. A correction is applied to the collimation error, i.e., the deviation of the Horizontal Axis, or Vertical Axis, or Sight Axis.

Scanner Error Distribution

Ideally all axes are perpendicular in respect to each other as shown below, but in reality this is not possible and corrections must be applied.
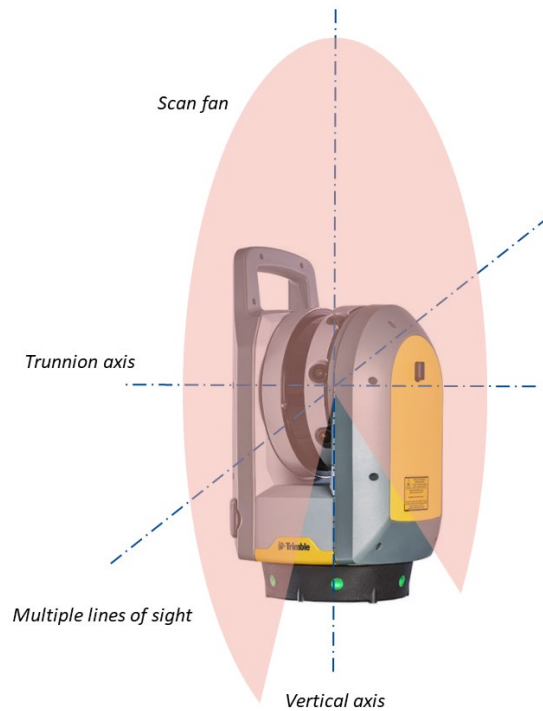

Step 1: Determine the trunnion axis error. When the trunnion axis is not perpendicular in respect to the vertical axis the scan fan becomes tilted.
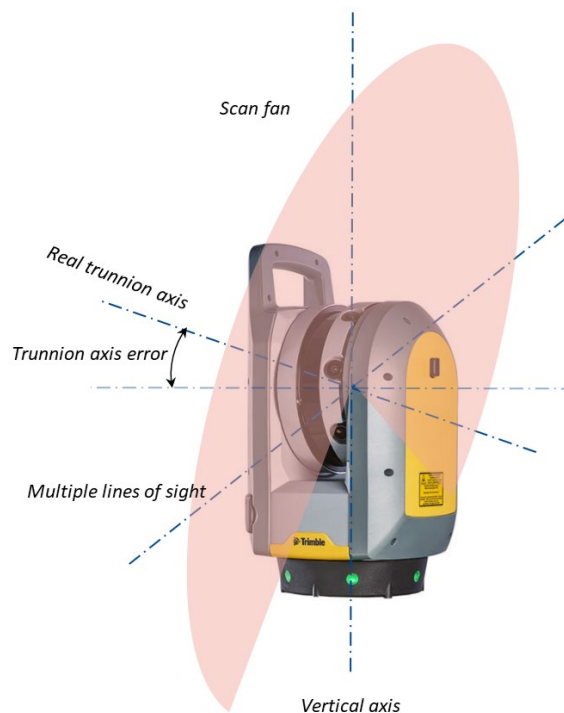
Step 2: Determine the error in the deflection mirror. When the 45° deflection mirror angle is not exactly 45° the scan fan becomes a tilted cone.
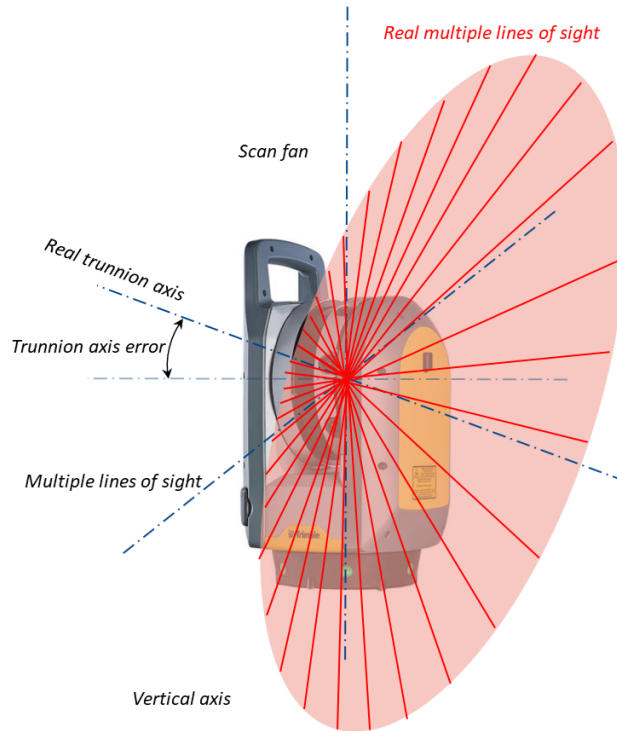
Step 3: Determine the error with alignment of the deflection unit motor axis. When the deflection unit motor axis is not aligned exactly with the laser beam the tilted cone will now have a sinus on top.
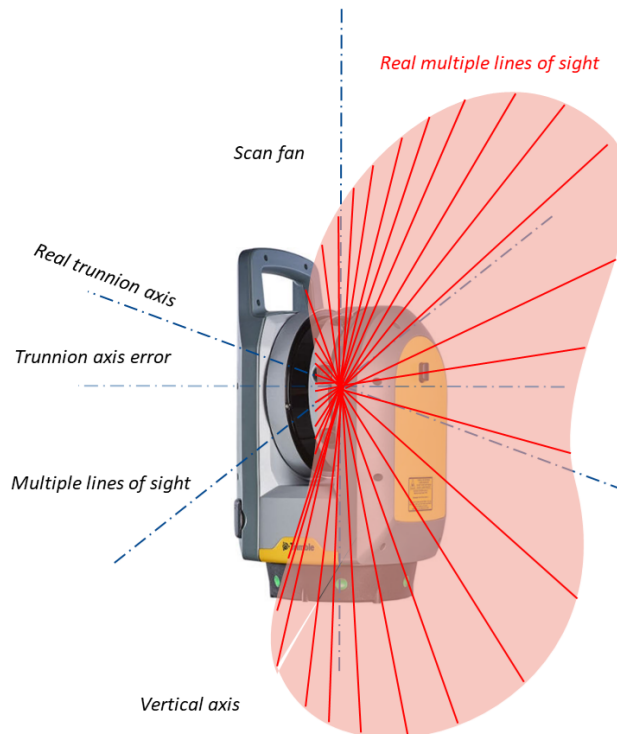
Collimation Modes

The internal collimator is used in two different modes to perform the automatic calibration.

- Auto collimation mode - internal collimator camera measures the center unit mirror to the front and back side for the trunnion axis error.
- Collimation mode – internal collimator camera measures EDM shots over the vertical deflection angle for horizontal & vertical collimation errors.

Internal Collimator Measurements and Calculations

Measuring horizontal and vertical collimation errors of the sighting axis is an automatic process of positioning the vertical telescope movements so that the laser sighting axis points directly into the nadir. The laser spot will be identified with the internal collimator camera in the base unit and will be measured with the center of gravity. Keeping the vertical position as it is, the instrument will turn a full circle horizontally measuring permanently the spot position on the camera chip. The given figure of the spot will be exactly a circle with a center representing the vertical axis.

At least two measurements are required for constant horizontal angle and different vertical directions. Both points are defining a line. The foot dropped perpendicular from the circle center will be calculated. The deviation equates to vertical collimation error. The distance between circle center and the foot print defines the blind spot or the sum of the instrument trunnion axis error "k" and horizontal collimation error "c". In case the trunnion error is known the horizontal collimation error can be calculated.
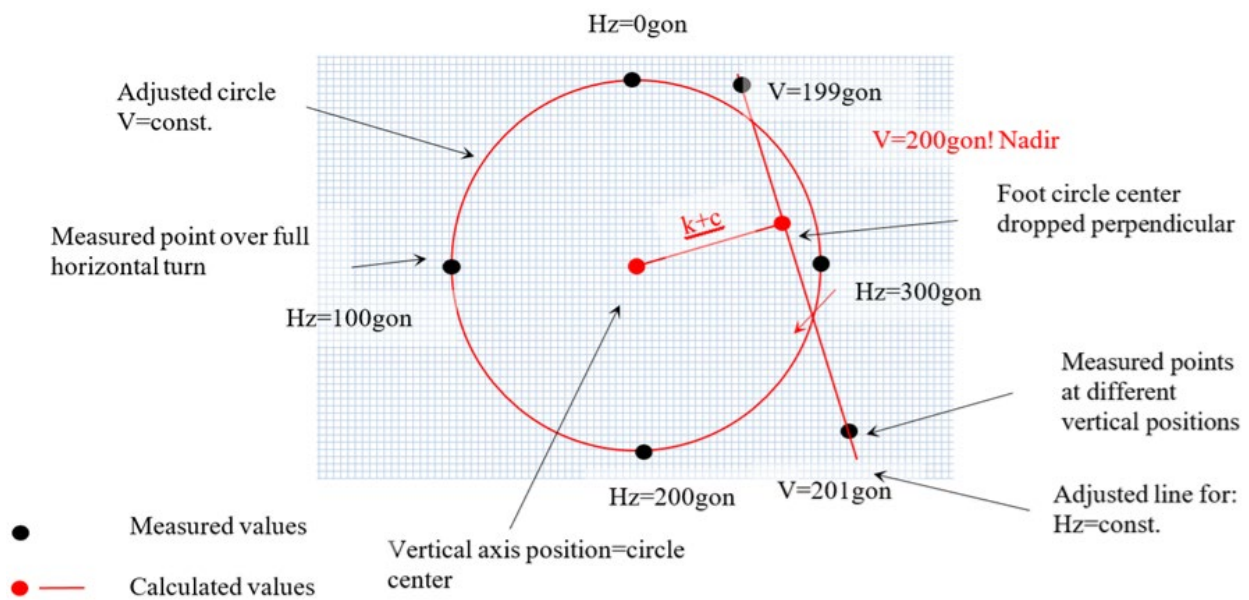

Figure 4: Internal Collimator Measurements and Calculations

Automatic Distance Calibration

The Electronic Distance Measurement (EDM) is a key component to the performance of a 3D laser scanner. A high quality 3D point cloud is dependent on the EDM performing consistently and reliably over extreme working conditions. In the X7, Trimble has integrated proprietary technology in order to guarantee a survey-grade measurement performance for its customers. One of the challenges to address is to guarantee a range accuracy over the lifetime of the instrument, at all temperatures and for all target reflectivity. In order to achieve this, Trimble has integrated into its EDM an innovative calibration routine that is carried out before every scan.

The X7 EDM is based on the principle of pulsed time-of-flight. In figure 5 we show a schematic representation of the EDM.
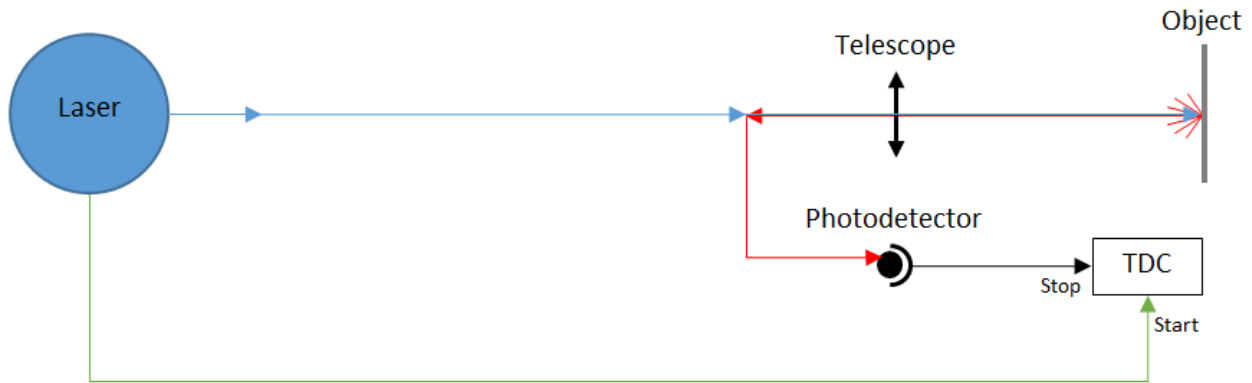

Figure 5: Schematic of EDM

The laser is triggered to send a high power laser pulse. At the same time a "Start" signal is sent to the Time-to-Digital Converter (TDC) to start the "stopwatch". The laser pulse travels to the object to be measured at the speed of light. A small amount of the laser pulse is reflected off the object and travels back into the telescope and is detected by a photodetector. The photodetector measures the signal level and sends a stop signal to the TDC, which stops the "stopwatch", and the time-of-flight of the laser pulse is measured. This is then converted to a measurement of distance. The X7 operates between a large temperature range of -20°C to 50°C. In addition it has a very large dynamic range, meaning that it can detect both very weak and very strong optical signal levels. In order for the X7 to measure accurately the absolute distance, it uses an innovative auto-calibration technique.

In figure 6 we show the modified schematic of the EDM whereby a copy of the emitted laser pulse is sent through a calibration line.
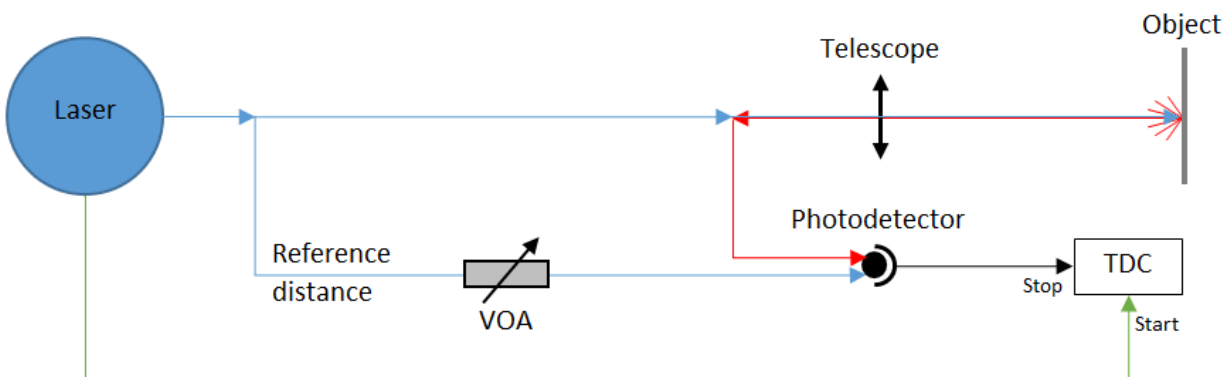

Figure 6: Schematic of EDM with calibration line

This calibration line has an extremely stable calibrated reference distance and has a built-in Variable Optical Attenuator (VOA), which allows us to modify the pulse signal level. Before each scan is initiated, we measure the distance given by pulses passing through the calibration line for all possible signal levels. The result of such a calibration is shown in figure 7.
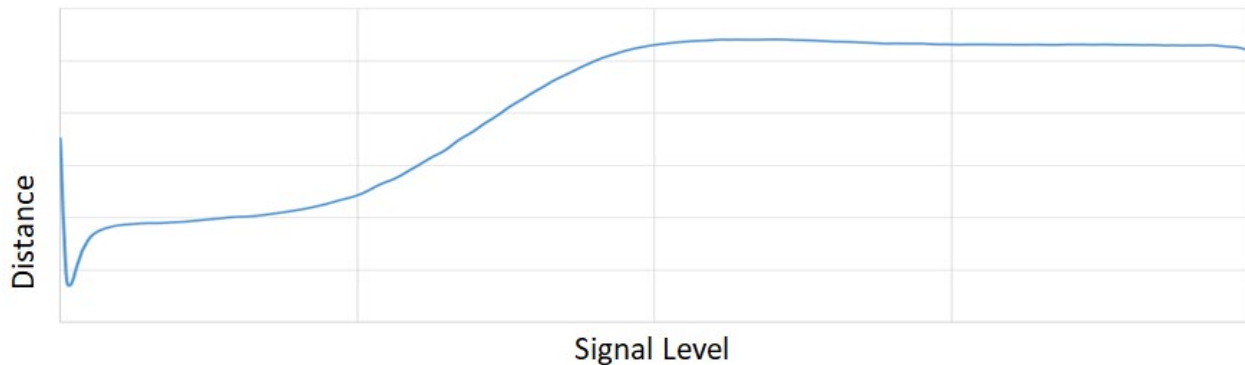

Figure 7: Distance correction look-up table

As we know the physical reference distance of the calibration line we know the distance offset correction that must be applied for a distance measured with a given signal level. Therefore, when we carry out a 3D scan, for each distance measured, we use the pulse signal level to apply a distance correction according to the Look-Up-Table given by figure 7.

Thanks to this innovative approach, X7 users can have confidence that every scan in all conditions will give them the quality data that they expect.

Smart Calibration

The auto-calibration feature is smart and monitors environmental temperature, ambient light, vibration, instrument temperature and vertical speed to optimize the process. Under normal conditions full automatic calibration will take approximately 25 seconds and under the worst conditions like extreme ambient light or vibration from the ground or wind, the process will automatically adapt and cover up to 45 seconds. The system will effectively compensate for the temperature range and after temperature stabilization the calibration time will decrease and may not have to be run at all. The instrument can even adjust to a normal level of shocks and vibration after transportation. Internal and external conditions are continuously monitored and a watch dog will perform a calibration refresh if required to stay within the accuracy range.

Smart automatic angular and distance calibrations ensure consistent data quality without the maintenance cost, downtime and hassle associated with annual calibrations.

Note: Even though the smart calibration feature can help compensate for shock and vibration, users should take care when handling the instrument. Follow the instructions in the user guide for care and maintenance and good station setup practices.

Impact on Return on Investment

The Trimble X7 auto-calibration and mechanical design features lower the cost of ownership and reduce downtime for faster ROI. Annual calibration service for scanners can range from $3,500-$6,000 after the first year of ownership. That's an average calibration cost of $19,000 after five years and it doesn't include shipping cost or lost revenue from downtime. Companies will cover the cost of annual calibrations with extended warranties, but the average cost of a warranty is $5,200 so you can expect to pay approximately $20,800 for four years of coverage. The Trimble X7 is the only scanner on the market with a two year warranty so you won't need to consider a warranty until year three and the X7 warranty is under half the cost of the industry average.

Now let's talk about loss of revenue from downtime. Calibration service typically takes 2-3 weeks and this doesn't include shipping time. In general, you can expect to have the scanner out of business for one month. The average day rate for a scanner is $1,500 so depending on the amount of work you have during the service period you could be looking at a loss of up to 20 working days or $30,000. Even if you only employ the scanner for 2-3 days/week you're losing $12,000-$18,000 in revenue during the month of service.

If you consider the savings from no annual calibrations, less downtime and lower warranty cost, one X7 scanner can potentially save you enough money in five years to buy one or two more scanners, just from lower maintenance cost.

Summary of Features and Benefits

Features	Benefits
Automatic Calibration	• Ensures data accuracy from scan to scan • Angular and distance correction • Alidades encoder system adopted from total stations for precision • Accounts for alignment deviations inside the scanner head and adjusts to vibration and even shock • Smart calibration monitors environmental conditions and instrument temperature and vertical speed • Smart calibration only applies correction when required • No targets or user interaction required • No need for annual calibrations reduces cost of ownership and accelerates ROI • Enables industry leading 2 year warranty
Protected Center Unit*	• Integrates high speed deflection unit for scanning, internal tilt sensors, EDM source, camera system and laser pointer in one protected center unit • Optics protection in all weather conditions (IP55) • Safe operation
X-Drive Vertical Deflection Drive*	• Integrates survey grade servo drive with high speed scanning • Concept of a vertical servo system enables the entire center unit to rotate around the trunnion axis • Enables automatic calibration and self-leveling • Reliable; long life; low friction, vibration, power consumption and noise • Enables industry leading 2 year warranty
Automatic Self-Leveling*	• Survey grade level compensation for both upright and upside down orientations within range of ±10° • Survey grade accuracy <3" = 0.3mm @ 20m • Scans with <45° tilt have coarse grade level accuracy • Real time level monitoring will not allow scan acquisition >45° tilt and will stop scans when level is disrupted • Verify verticality and levelness with confidence • Supports in field registration
Integrated Camera System*	• 3 x 10 MP cameras for fast image acquisition of 1-2 min • Quality full panoramas and scan colorization • Calibrated, coaxial cameras with optical axis aligned to center of deflection mirror to minimize parallax between images and scans • HDR and white balance correction to ensure image quality
Laser Pointer	• Geo-referencing • Single point measurements

* See the White Paper - Inside Trimble X7 X-Drive Technology for more details on this feature.

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