A Comparison of Techniques for Collecting Elevation Data

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Date

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Problem Statement

Several types of equipment and methods are available to the modern surveyor for the purpose of collecting elevation data. An overview of the equipment and methods available at my employer, as well as estimates of their accuracy is presented herein. Different equipment and procedures provide different accuracies and can involve varying degrees of effort to collect and process the data, which all affect the relative expense for the acquisition of the data.

The equipment and procedures described herein encompass the types of equipment available at my employer, including associated data processing software, and methods for quality control. A comparison of the techniques reveals varying capabilities for accuracy, specifically targeting the range of ±0.005ft to ±0.10ft. Finally, there is a comparison of relative cost for the different techniques.

I. Introduction

A variety of data collection techniques can be used by a surveyor to capture elevation data; the selection of equipment and method is largely tied to the desired accuracy of the data. In general, there is a trade-off between speed and accuracy, although both are also associated with the equipment used, which also comes at a cost. Equipment not only refers to the equipment used to collect the data, but also the computers and software used to process the data. The purpose of this paper is to compare data collection techniques available to my company that provide elevation accuracies from ± 0.005 ft to ± 0.10 ft under various conditions. This includes an evaluation of the equipment itself, field and office procedures, quality control, and relative costs.

The accuracy of the ground collection techniques (level, robotic total station, and GNSS) associated with a datum is predicated on the FGCS classification of the control points that are included in the project, and also their proximity to the project. Establishing a vertical control network begins with one or more benchmarks (depending on the procedure). Whether using one or multiple benchmarks, the overall accuracy of the survey cannot exceed the FGCS classification of the lowest-class/order benchmark included in the series. This is applicable to all surveying methods, and further detail is provided with each of the method descriptions.

The equipment that is available at my employer for the collection of elevation data includes:

Table 1 - Equipment List

Equipment	Relative Equipment Cost	Data Collection Speed	Data Processing	Relative precision
Using County LiDAR Data	Low	Fast	Download point cloud or contours to Civil3D	Low
Trimble R10 GNSS receiver	High	Medium	Download point file to Civil3D	Fair
Trimble S7 Robotic Total Station (1" angle)	High	Medium	Download point file to Civil3D	Good
SpectraPrecision DiNi Digital Level	Low	Slow	Download to spreadsheet or Civil3D	Excellent
TopCon Automatic Level	Low	Very Slow	Manual or entry to spreadsheet	Excellent

II. LiDAR data collection and data use

Light Detection and Ranging (LiDAR) data comes from aircraft that is equipped with laser scanning equipment, an inertial navigation system, a GNSS receiver, and a computer. The aircraft flies along a path that is tracked by the GNSS receiver, and laser pulses are transmitted to the ground below. The reflected pulses are used to determine range from the sensor to the reflected object, and when combined with the aircraft's position and attitude angles (yaw, pitch, and roll), a 3 dimensional coordinate of each ground point is determined (Charles D. Ghilani Section 27.18). As this system relies on GNSS, its accuracy cannot exceed that of GNSS.

LiDaR data is initially attractive because it can provide dense data for a large area, and in the case of my county, the data can be downloaded without cost to the user (although some counties charge a fee for this data). The point cloud data can be downloaded into Civil3D, parsed down to the specific project area, and used produce a surface model in under an hour. The vertical accuracy of LiDaR relies heavily on the nominal pulse spacing (NPS), which defines the density of the point cloud produced. The user of the data is also subject to the age of the data, as it was likely collected well before any particular construction project was identified. The user must determine if the LiDaR data is representative of the current surface, or that if the surface has already changed since the data was collected and is therefore invalid. LiDaR data for our location was collected by Ayers Associates from March 21, 2015 to March 31, 2015, and was collected to create 2-ft contours to meet FEMA vertical accuracy standards (Wood County).

This method would require roughly 2 hours for a technician to identify the site, download and parse the data for the site, and import the data into Civil 3D. No other technique described in this research can acquire data as quickly as the LiDaR method, but the data will lack references to ground objects such as benchmarks, trees, building corners, etc, and will not have breakline data that could be important to refining the surface for the purpose of evaluating surface flow. However, if the data required is used only for the purpose of observing rough topography, this method may be sufficient. While LiDaR provided by the county is a cost-effective method to create a rough surface model that has some applications, the focus of this research is on techniques that provide accuracies much better than this, so it will not be discussed further.

III. GNSS data collection and data use

The GNSS technique is the first technique that falls within the scope of accuracies described in this paper. GNSS surveying can be performed with a single survey-grade GNSS receiver and a cel phone with access to the Wisconsin Continuously Operating Reference Station (WISCORS) network, which has more than 80 GNSS reference stations across Wisconsin's 72 counties at a spacing of roughly 50km. The WISCORS network can provide accuracy as good as 2cm in real-time and eliminates the need for setting up a base station (Wisconsin DOT). We typically use a base station and localize our site to local GNSS benchmarks, but comparison of the two methods shows there is only a small improvement in precision when using a base station if proper care is taken. Even when using WisCORS, it is still our procedure to confirm the coordinates on a control point at the beginning and end of an observation session.

Localizing to local benchmarks requires identification of benchmarks on the NGS website, setting up the base station in a location mutually convenient to the site of interest and the benchmarks, and visiting the benchmarks. Coordinates for NGS stations are in geocentric (X, Y, Z) and state plane (N, E, Z) format, where we typically use Wisconsin County (N, E, Z) coordinates. The data collector will make the transformation to county coordinates, but it is important to make sure the correct geoid is applied. Our base station has a range of 0.5 miles when operated independently, or 5 miles when using a 25 watt repeater, which has been sufficient to reach an NGS point from any location we have attempted. NGS provides the online positioning user service (OPUS) that can be used to localize a site when no control points are used for calibration. This is a static observation technique, but the base can simultaneously be used to collect data that must be postprocessed.

Using the base introduces the possibility of setup errors, in the form of tripod miscentering, equipment errors (tribrach level out of calibration or tripod legs loose), or mistakes such as misreading antenna height and incorrect identification of the station. These should be identified when the user attempts to localize with the control points. Proper procedure also includes a closing check at the termination of the survey and periodic checks throughout the observation window. There are sources of error associated with the rover that can occur when using the base or WisCORS, and include calibration of the level bubble on the pole, confirming that the joints on the pole are snug, and errors internal to the instrument that require sending it in for service. Since the equipment we use is used only intermittently, it is checked when it comes into our posession, with the exception of the receiver's internal level calibration that must be recalibrated every 30 days. The equipment is shared with other employers, who each perform calibration checks on their projects. The specifications for the Trimble R10 GNSS unit report an accuracy of 15mm (.05 ft) vertically (Trimble Geospatial), but if WisCORS is used, the 2cm accuracy translates to 0.067ft. This is the best that can be expected in normal conditions, but in either case, this will degrade when conditions become adverse. The GNSS method produces the coarsest vertical precision within the scope of this paper: under ±0.10ft.

When beginning work on a new site, it is imperative to check the calibration of the site by taking observations on a known benchmark and comparing the observation to the published elevation. This observation should be recorded in the data collector as a check, and additional checks should be conducted periodically throughout the observation window. Localization can be performed by calibrating to a single NGS benchmark, but ideally to four or more with geometry that creates a polygon with the entire site of interest within the boundary of that polygon. This additional data will also help improve accuracy and reveal if any benchmark does not agree with the others (which will help identify errors). The periodic checks can be performed on a temporary control point set on the site and will reveal if the position of the base has changed due to tripod settling.

Before conducting a GNSS survey, it is wise to use planning software to identify an observation window when conditions are most favorable. The current number of satellites in orbit among the GPS, GLoNaSS, and Galileo constellations will usually produce conditions where there are sufficient viewable satellites in the sky with satisfactory geometry for observations within the ±0.10ft tolerance. Trimble provides an online resource to check satellite availability and geometry. Local observations for August 16, 2019 are provided in Figure 1 - Number of Satellites on August 16, 2019 and Figure 2 - DOP Chart for August 16, 2019. The fewest satellites observable in the day occurs at 13:50, with 17 visible satellites. Theoretically, observations can be made with as few as 5 satellites if their geometry has them well distributed in the sky, but that would not likely produce the desired accuracy, and leave the user in a precarious position that the momentary loss of a single satellite would terminate the ability to collect data. In 2019, it is unlikely that the number of satellites available will be insufficient at any time. It is more critical to check the Dilution of Precision (DOP) chart, which will be adversely affected if satellite availability diminishes. On August 16, 2019, the DOP chart indicates a spike to 2.6 just before 6AM. A spike of this magnitude is not concerning, as it is still well below 4.0. 4.0 is a threshold often seen as a point when accuracy will degrade. In this case, the DOP is satisfactory all day.

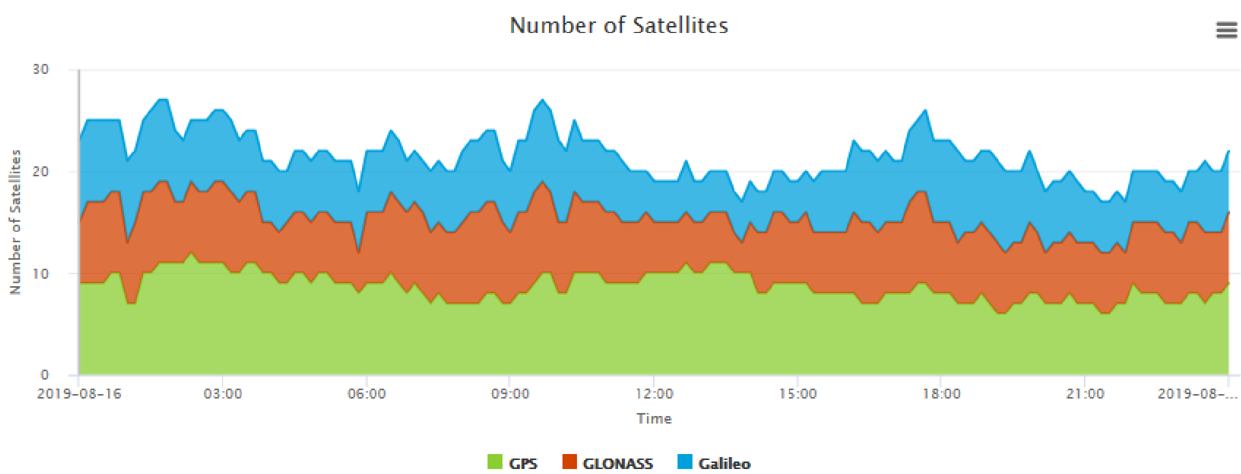

Figure 1 - Number of Satellites on August 16, 2019

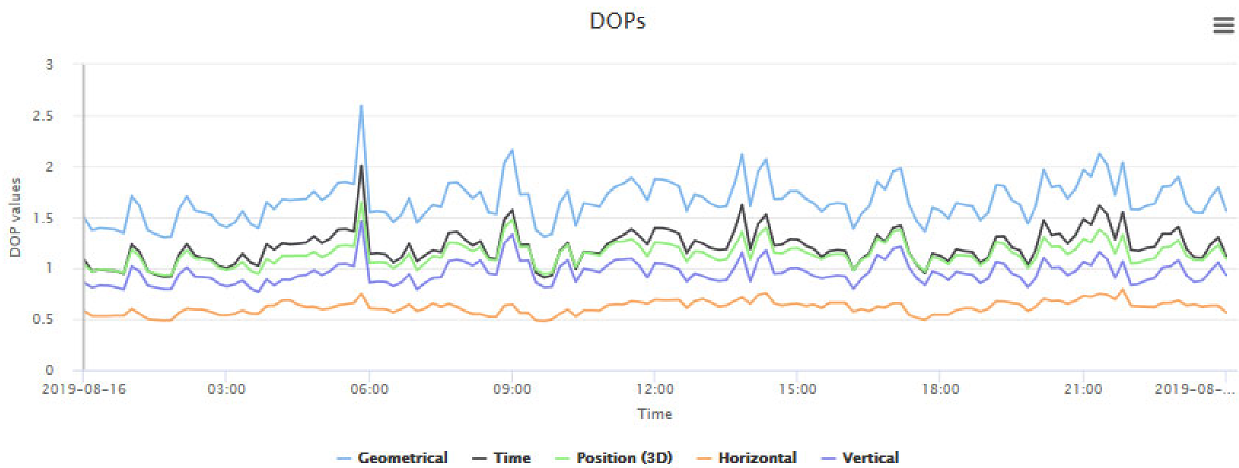

Figure 2 - DOP Chart for August 16, 2019

In addition, it is also wise to check for ionospheric activity that could cause refraction. A summary chart is available on the Trimble planning website as shown in Figure 3 - Ionospheric Information for August 16, 2019 and from the Space Weather Prediction Center (National Oceanic and Atmospheric Administration) Table 2-K-index for August 16, 2019. These two sources provide somewhat different results. The Trimble site indicates an Ionospheric Index of 1 throughout the day. The SWPC website indicates K-index values of 1-3 throughout the same period (marked in a box to adjust UTC to local time). Either way, the acceptable threshold of 4 is not violated.

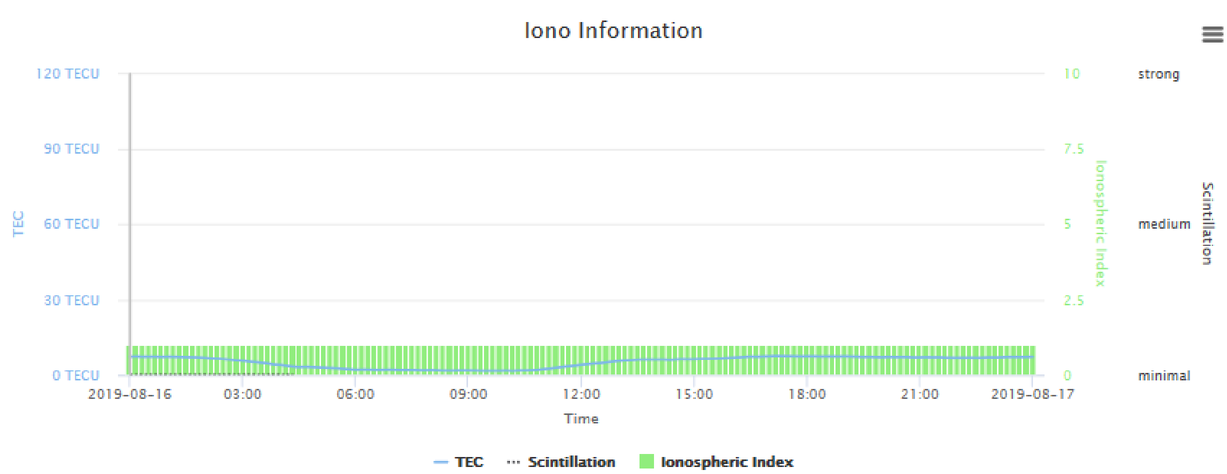

Figure 3 - Ionospheric Information for August 16, 2019

NOAA Kp index breakdown Aug 16-Aug 18 2019

	Aug 16	Aug 17	Aug 18
00-03UT	2	2	2
03-06UT	1	1	2
06-09UT	1	2	2
09-12UT	1	1	1
12-15UT	2	1	1
15-18UT	3	1	2
18-21UT	2	2	2
21-00UT	3	2	2

Table 2-K-index for August 16, 2019

GNSS surveying has some considerations for local conditions as well. Geoid heights for the site must be known and correctly applied. Tree canopies and other vertical obstructions can occlude the view of portions of the sky, which not only reduces the number of visible satellites, it gives the remaining satellites less desirable geometry since the visible satellites are in a smaller portion of the sky. The user must be wary to this condition and watch the PDOP on the data collector. It can also be set to warn the user about PDOP exceeding a preset threshold, which is often set to 4.0. The user must also be wary of vertical obstructions like walls or chain link fences that produce a phenomenon called multipathing. Multipathing occurs when the receiver receives a signal directly from a satellite as well as one that bounces off a vertical surface. They have different paths to the receiver (the reflected one is longer), and this causes the accuracy of the data to diminish. When the data is downloaded, there is metadata associated with each point, which includes horizontal and vertical precisions, number of satellites, and PDOP at the time the data was collected. This can be reviewed if any of the data is questioned.

Once the user has a satisfactory understanding of the limitations of GNSS surveying, they can evaluate how much of the site can be observed using this method. In many cases, there will be portions of the site where GNSS data collection is not practical, most likely due to tree canopies. In this case, the GNSS equipment will be used to set control near the area that cannot be observed by GNSS so that a total station can be used to collect the remaining data in the area where GNSS could not be used. Total station surveying will require a minimum of two control points that are visible from each other, and additional control points must be set with the GNSS equipment if a single instrument placement is insufficient to collect the missing data.

If the site is free (or nearly free) from significant tree cover, power lines, buildings, and other obstructions that would block the view of satellites, GNSS is the most cost-effective way to collect site data. It can be performed by a technician working alone and will produce a point file that includes horizontal coordinates attached to vertical coordinates with an accuracy of around ±0.08ft, meeting the ±0.10ft threshold. If necessary (due to canopy restrictions), the same technician can set control points with the GNSS equipment and use a robotic total station to complete the data collection task. This can be done with the same data collector, resulting in a single data file that will be passed on to the Civil3D technician to generate a surface.

IV. Robotic total station (trigonometric leveling) data collection and use

Trigonometric leveling is performed with a total station and can achieve accuracies better than the GNSS equipment. The Trimble S7 has a published accuracy 1" angles, a standard prism accuracy of 2mm + 2ppm, and a range of up to 250m (820ft) (Trimble). In short, the vertical accuracy of data produced by this instrument will diminish as the range from the instrument increases, and also as the elevation difference between the instrument and prism increases. On a level surface, these specifications suggest that the equipment's angular precision alone will produce elevation errors of ±.005ft at a range of 1000ft. Using Equation 1 - Vertical Distance for Trigonometric Leveling for several distances, Table 3 - Vertical error due to instrument angle precision can be produced.

$$Vertical\ distance\ error = slope\ distance * \sin{(angle\ error)}$$

Equation 1 - Vertical Distance for Trigonometric Leveling

Table 3 - Vertical error due to instrument angle precision

Range (ft)	Elevation accuracy for 1" error near horizontal
25	0.000
50	0.000
100	0.000
150	0.001
200	0.001
250	0.001
300	0.001
400	0.002
600	0.003
800	0.004
1000	0.005
1250	0.006
1500	0.007
1750	0.008
2000	0.010

While the angular precision of the instrument introduces only a small amount of vertical inaccuracy, the error is increased by errors in measuring instrument height, rod height, and also the level bubble on the prism pole (which affects how plumb the instrument is). The instrument height can easily contribute another 0.01ft to the elevation accuracy; the error at the pole can be minimized by using one of the indexed rod height positions. The combinations of these errors should be realized when the user checks their setup by checking in on a known control point, and this should be repeated periodically throughout the observation window.

The robotic total station has benefits compared to the other instruments. Data collection is faster than by either of the levels and is similar in speed to the GNSS unit. The RTS has a longer range than the levels (but shorter than GNSS), and the laser can find its target through small openings in vegetation where a level rod could not be read. When sights are long, it is important to make sure the data collector is set to adjust for curvature of the earth. Equation 2 – Curvature (Charles D. Ghilani Section 4.4) is used to calculate curvature (C_f) for distances measured in thousands of feet (F). Table 4 - Vertical Error Due to Curvature of the Earth shows the increase in error as distance increases.

$$C_f = .0239F^2$$

Equation 2 – Curvature

Table 4 - Vertical Error Due to Curvature of the Earth

Distance (ft)	Error (ft)
200	0.001
300	0.002
400	0.004
500	0.006
600	0.009
800	0.015
1000	0.024
1500	0.054
2000	0.096

The RTS can be used under tree canopies and near walls, where these are limitations of the GNSS unit. It can also be used in areas where the elevation change is significant over a short distance, which is a challenge for levels. However, unlike the level, the total station also collects horizontal coordinates for each point, so it is much easier to download the data and create a topographic map in modeling software such as Civil3D.

In summary, this method will produce elevation data with an accuracy of ±0.04ft (an improvement over GNSS) and will also produce a point file with horizontal coordinates attached to each point. It can be performed by a single user and can be used in areas that are limitations for GNSS equipment (tree canopies, building faces, power lines), and levels (significant elevation changes). Ground level line-of-sight is a limitation for RTS that is not present for GNSS. Since a line-of-sight to the instrument must always be maintained by the rover, it may require setting up the equipment in several locations, which requires setting more control points in advance. A minimum of two control points are needed to begin total station work, with a traverse running between them to set control points on the site.

V. Single-wire leveling data collection and data use

Single-wire leveling can be performed with an automatic level, and can achieve an accuracy of ±0.03ft. Standard procedures include balanced sights, closed loops, and finally, determining and adjusting for misclosure. The nature of the level creates a challenge if the elevation varies significantly, as the end of the rod (particularly the bottom end) may not be visible, or the top end may sway as it is extended to longer lengths.

Balanced sights are important to leveling because this technique can negate the effects of collimation errors that may exist in the instrument as well as systematic errors due to the earth's curvature. A collimation error occurs when the axis of sight is not aligned with the horizontal axis, which is to say that the instrument is actually not horizontal when the level bubble indicates that it is; this can occur even in instruments is compensators (automatic levels). If the foresight and backsight distances are equal, then the collimation error created on the foresight and backsight are equal, as shown in Figure 4 - Balanced Sights (Webster). Since the backsight is added and the foresight is subtracted, then these two errors of equal magnitude have a net effect of zero in the elevation calculation. This technique will also save the user from needing to make corrections for curvature, since the effect of curvature will also be negated when the foresights and backsights are equal.

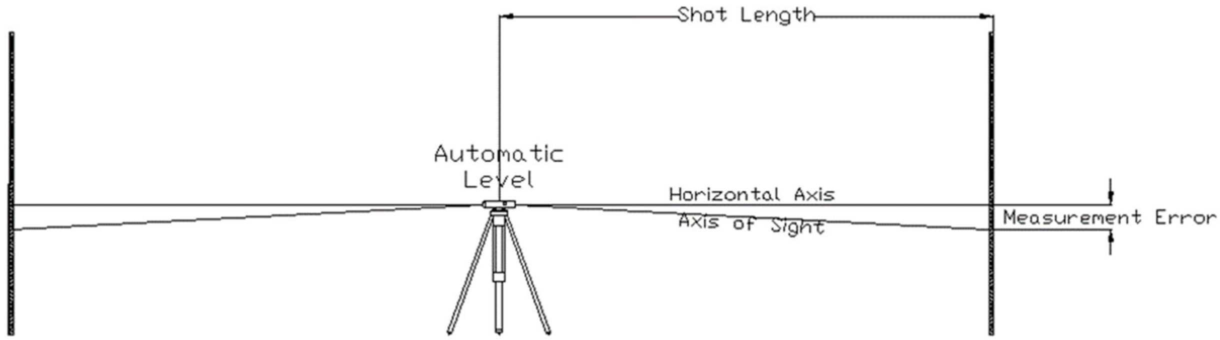

Figure 4 - Balanced Sights

When creating a series of benchmarks in leveling, it is preferable to make short closed loops returning to the point of beginning, as shown in Figure 5 - Closed loop (Webster). It is expected that the finishing elevation will match the starting elevation (because it is the same point), but small errors due to rounding are acceptable. If a large error occurs, this procedure minimizes the amount of work that has to be repeated. In the end, many of these small loops will be interconnected to form a network of control points, as shown in Figure 6 - Multiple small loops (Charles D. Ghilani Section 19.14) where points X, Y, and Z are networked from BM A & BM B. Lines 1 through 4 are sufficient to determine the elevations, but the addition of lines 5-7 provides redundancy and the ability to discover the source of error without repeating all four of the other loops.

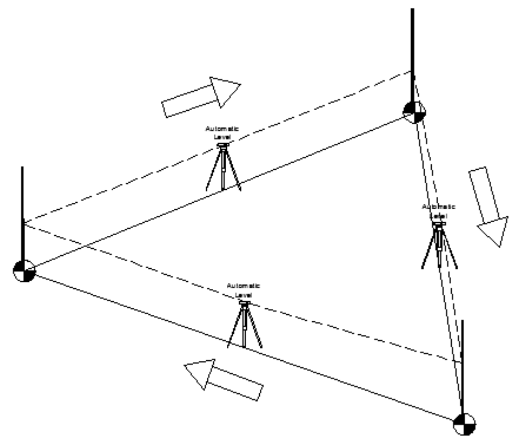

Figure 5 - Closed loop

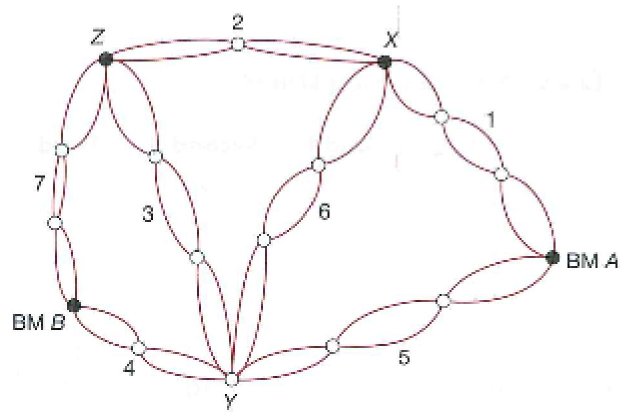

Figure 6 - Multiple small loops

After completing each loop, the misclosure must be calculated, and adjusted if it falls within tolerance. The Wisconsin DOT provides Equation 3- Single wire adjustment (Wisconsin DOT FDM 9-40-25.1), which is used to calculate the adjustment that is applied at each calculated elevation. It distributes the total error over all of the turning points, and provides an adjustment that gradually approaches the total misclosure, increasing in magnitude through each turning point. An example is shown in Table 5 - Single Wire Adjustment (Webster).

$$Adjustment = Misclosure \times \frac{Number\ of\ turning\ points\ to\ a\ given\ TP}{Total\ number\ of\ TP's}$$

Equation 3- Single wire adjustment

Table 5 - Single Wire Adjustment[1]

Point	BS	HI	FS	Elev	Adj Elev
A	4.47			1000.00	1000.00
		1004.47		(+.0043)	
B	3.48		2.86	1001.59	1001.59
		1005.07		(+.0086)	
TP1	8.36		4.03	1001.04	1001.05
		1009.40		(+.0129)	
TP2	6.63		5.22	1005.18	1005.19
		1011.81		(+.0172)	
TP3	3.88		11.61	1000.20	1000.22
		1004.08		(+.0215)	
TP4	4.79		6.33	997.75	997.77
		1002.54		(+.0258)	
TP5	5.90		5.49	997.05	997.08
		1002.95		(+.0301)	
A			2.98	999.97	1000.00

Weather conditions also play a role. Refraction occurs in bright light; the bright sun causes the line of sight to bend with the curvature of the earth. Ideally, this would also be performed on a cloudy day (or with something to shade the instrument from direct sun) to mitigate the effects of refraction (Charles D. Ghilani Section 19.14). A day with calm wind is also ideal, as the wind can cause the tripod to move slightly.

[1] Misclosure = -0.03ft, distributed over 7 turning points is +0.0043ft per TP

The equipment should also be calibrated (peg testing) to reduce the possibility of introducing collimation errors.

It is unlikely that this technique would be used to collect dense survey data over a large area because it is labor intensive. This technique will require two technicians on site. If a data to generate a surface is necessary, a level alone could be used to establish a rectangular grid of points with regular spacing up to 450ft, and the time required to collect the data will increase if the site is not relatively flat or requires clearing line-of-sight. If the grid method is used, it will still be necessary to capture points along the grid lines, perimeter, and where grade breaks occur. Figure 7 - Grid Points and Interpolation shows that contour 58.0 can only be surmised by linear interpolation between the points of known elevation if the breakline is not observed. (Nathanson, Lanzafama and Kissam 212-3). If the grid method were used with a radial survey technique, the speed is increased but accuracy degrades because the lengths of sights are not balanced. The same grid points are shown in Figure 8 - Radial Survey, and the loop including the existing BM, new BM, and TP 1 has balanced shots, but each of the two setups within the site has multiple points radiating from it that are not included in loops. Including them as observations from the other instrument setup would create a check on each point but the sights would not be balanced so adjustments are necessary to account for curvature. The grid spacing would be smaller than the previous technique, since the longest shot cannot exceed 300ft, with traverse stations not exceeding a spacing of 500ft (Nathanson, Lanzafama and Kissam 212-4).

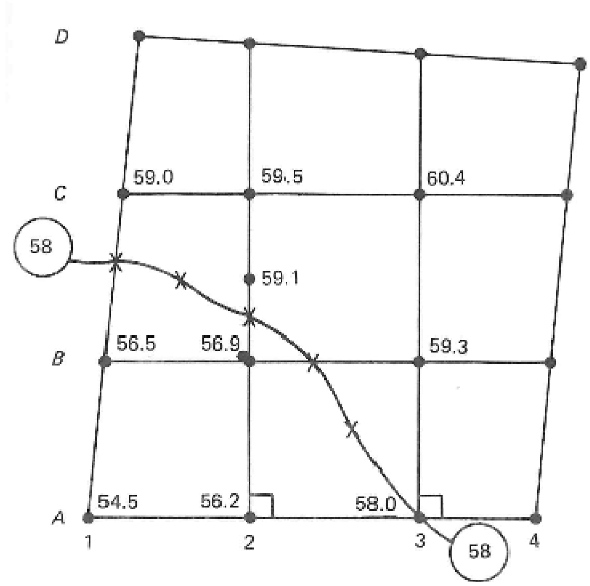

Figure 7 - Grid Points and Interpolation

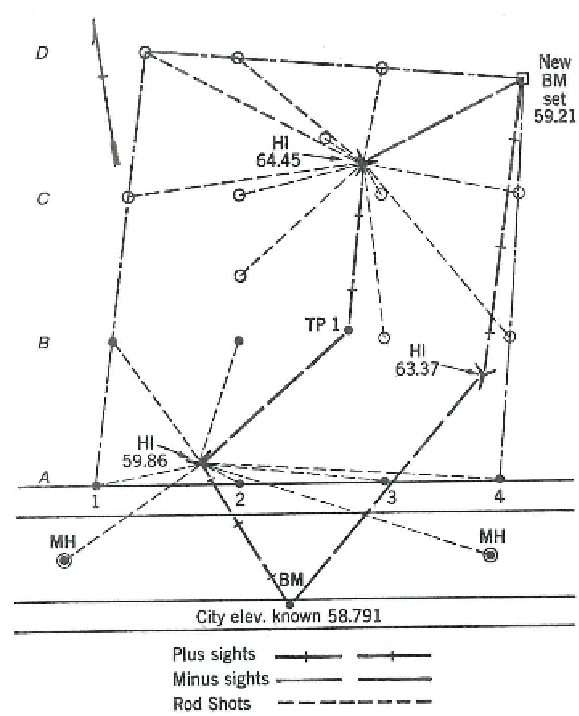

Figure 8 - Radial Survey

VI. Precise leveling data collection and data use

Precise leveling is necessary to achieve the ±0.005ft elevation accuracy in the scope of this paper. Precise leveling is a combination of techniques and equipment needed to achieve the highest possible accuracy. This process includes using levels to establish a vertical control network using precise techniques, and adding additional data as needed to provide the required point density. Precise leveling can be achieved with an automatic level or a digital level. The digital level is faster because the data is recorded in the instrument's memory and can be downloaded; the automatic level requires manual data recording. If this data will also be used for mapping, then the horizontal coordinates of each point must also be obtained. In this case, a total station would be used to collect Northing, Easting, and preliminary elevation data for points that are not on the grid. The elevation data would later be updated with the elevations obtained by precise leveling. However, it is more likely that precise leveling would only be used to set benchmarks, and not for complete topographic data. Precise leveling may be necessary to check slight changes in grade, which can occur in pipelines, road gutters, road cross sections, or superelevated curves. In these instances, precise measurements are necessary.

There are several techniques that are necessary to achieve precise leveling, which include balancing sights, 3-wire recording, running closed loops, and finally, determining and adjusting misclosure. Similar to single-wire leveling, regular equipment calibration (peg testing) is imperative.

Balancing foresights and backsights, as explained previously, is critical to precise leveling to mitigate the effect of collimation errors, as well as avoiding curvature adjustments. Similar to single-wire leveling, accuracy is improved if the work can be done on a day when the wind is calm (to avoid vibrations due to wind) and the sky is overcast (to avoid refraction). The Wisconsin DOT also specifies that the minimum ground clearance for the line of sight is 1.6ft when using 3-wire leveling (Wisconsin DOT FDM 9-40 Attachment 2)

Three-wire leveling is a technique employed to improve the precision in leveling. Instead of reading only the middle wire, readings are taken on the level rod at the top, middle, and bottom wires seen on the reticle, as shown in Figure 9 - Three Wire Leveling (Webster).

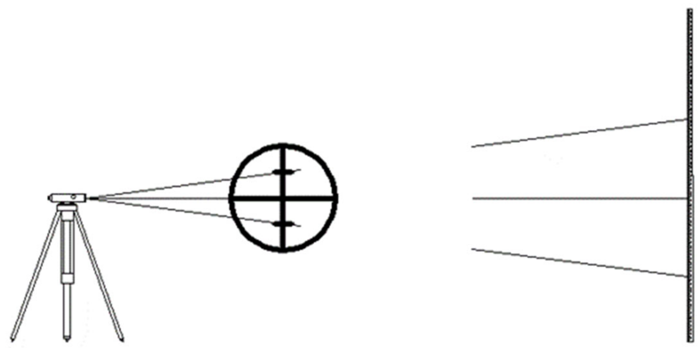

Figure 9 - Three Wire Leveling

This gives the user the opportunity to immediately identify a rod reading error because the difference between the top and middle wires should be the same as the difference between the middle and bottom wires (they may be off by 0.01ft due to rounding). If the readings satisfy this test, the average of all three readings produces a single reading but carried out to one more decimal place (0.001ft in this case). This is done for every observation in the loop. The observations can also be used to determine the length of each sight using stadia. The difference between the top and bottom readings, multiplied by 100, produces the length of the sight in feet. This helps the user ensure that the lengths of the sights are roughly equal. When using a digital level, the instrument scans a rod with a bar code on it, and in a similar way, determines the rod reading to 3 decimals as well as the distance.

The leveling should be performed in a series of closed polygon loops, and the misclosure of each loop must be calculated to determine if error is permissible or not. It is wise to run a series of small loops because any loop with a significant error has to be repeated until the misclosure is within tolerance. Any error that occurs must be adjusted, which is simply a technique to distribute the error among all of the shots. An example of data recording, determination of misclosure, and error adjustment with WisDOT calculation (Wisconsin DOT FDM 9-40-25.2) is shown in Table 6 - Three wire recording and adjustment (Webster).

$$Cumulative\ Adjustment = \frac{Cumulative\ traverse\ length}{Total\ Length}$$

Equation 4- WisDOT 3-wire Adjustment

Table 6 - Three wire recording and adjustment

Point	BS	Stadia	FS	Stadia	Elev (ft)	Adjusted El (ft)
CP N					1038.110	1038.110
	4.13		6.92			
	2.55	158	5.69	123	+2.553	
	0.98	157	4.47	122	1040.663	1040.662
	7.66	315	17.08	245	-5.693	
	+2.553		-5.693			
TP 1					1034.970	1034.969
	8.47		5.13			
	7.33	114	3.91	122	+7.333	
	6.20	113	2.68	123	1042.303	1042.301
	22.00	227	11.72	245	-3.907	
	+7.333		-3.907			
Hydrant 11					1038.396	1038.393
	7.04		7.91			
	5.23	181	6.18	173	+5.230	
	3.42	181	4.45	173	1043.626	1043.623
	15.69	362	18.54	346	-6.180	
	+5.230		-6.180			
CP X					1037.446	1037.442
CP X	True Elevation = 1037.442 (adjust to this)					
∑BS=	+15.116	∑FS=	-15.780			
Misclosure: 1037.439-1037.435=0.004ft						
Total Distance: 315+245+227+245+362+346=1740ft = 0.330mi						
Adjustment = 0.004*∑L/1740ft (where L is the length a line)						
Page Check: 1038.110+15.116-15.780=1037.446						

VII. Relative cost and recommendations

Recommendations for data collection methods are tied directly to the intent for the data and site conditions. If the project requires producing a digital surface, the GNSS and Robotic Total Station equipment will both meet the ±0.10ft accuracy level, and will produce points that have N, E, Z coordinates that can be downloaded into Civil3D. Both can be performed by a single technician, but the GNSS equipment is faster with some sacrifice of accuracy. If the site is an open field, GNSS would be the fastest and produce a surface with an accuracy under ±0.10ft. If there are areas where the GNSS equipment cannot be used due to canopy restriction or potential for multipathing, the GNSS equipment would used to set control points that could be used by the robotic total station without any degradation of the accuracy.

If a digital surface with greater accuracy is needed, then the GNSS equipment could be used to set control points with horizontal coordinates only. A local benchmark would be needed to run a level loop to determine the elevation of the control points and improve their accuracy. Using the corrected elevations, the total station would be used to survey the site with a precision approaching ±0.03ft if the benchmarks were set with 3-wire leveling, or perhaps ±0.05ft if they were set using single-wire techniques.

It is generally practical to only set benchmarks or grid points with the single- or 3-wire leveling techniques due the time expenditure in data collection. Smaller tasks, such as road cross-sections or slope for a slab-on-grade are other common uses for more precise elevation data; GNSS is not precise enough to set grade for paving or to verify cross slope or superelevation, but the total station is, particularly when sights are short. A crew of two will collect data in either method, and produce fewer, but more accurate data points than a single person could with a robotic total station or GNSS. The points would need to be revisited with

GNSS or Total Station if horizontal coordinates of the points were needed. The single-wire technique can approach ±0.02ft precision with proper care, and the 3-wire technique can approach ±0.005ft accuracy. If the site has considerable elevation changes, this becomes even more labor-intensive.

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Appendix A – Trimble S7 Product Data

DATASHEET

Trimble S7

TOTAL STATION

THE MOST PRODUCTIVE TOTAL STATION

The Trimble® S7 Total Station combines scanning, imaging and surveying into one powerful solution. Now you only need one instrument on the job site to perform all your data capture. Create 3D models, high accuracy visual site documentation, point clouds, and more using the Trimble S7, Trimble Access™ field software and Trimble Business Center office software.

The Trimble S7 is the ultimate system for efficient surveying, allowing you to adapt to any situation and increasing your productivity in the field. The combination of SureScan, Trimble VISION™, FineLock™ and DR Plus technology, along with many other features, means you'll be able to collect data faster and more accurately than ever before.

Integrated 3D Scanning

Save time in the field and in the office with Trimble SureScan technology. Now you have the flexibility to perform feature-rich scans every day. Efficiently capture the information you need to create digital terrain models (DTMs), perform volume calculations and make topographic measurements faster than with traditional surveying methods. SureScan technology enables you to collect and process data faster by focusing on collecting the right points, not just more points.

Improved Trimble VISION Technology

Trimble VISION technology gives you the power to direct your survey with live video images on the controller as well as create a wide variety of deliverables from collected imagery. Capture measurements to prisms or reflectorless with point-and-click efficiency via video. Quickly document your site and add notes directly to the pictures in the field to ensure you never miss that critical information. Back in the office, you can use your Trimble VISION data for measurements, or to process 360-degree panoramas and high dynamic range (HDR) images for even clearer deliverables.

Superior Accuracy with Trimble DR Plus

Trimble DR Plus range measurement technology provides extended range of Direct Reflex measurement without a prism. Now you can measure further with fewer instrument set-ups and enhance your scanning performance. Trimble DR Plus, combined with the smooth and silent MagDrive™ servo technology, creates unmatched capability for quick measurements, without compromising on accuracy.

Manage Your Assets

Know where your total stations are 24 hours a day with Trimble L2P technology. See where your equipment is at any given time and get alerts if your instrument leaves a job site or experiences unexpected equipment shock or abuse.

Trimble AllTrak™ software lets you view usage and keep up-to-date on firmware, software and maintenance requirements. With Trimble L2P and AllTrak, you can rest assured knowing your equipment is up-to-date and where it should be.

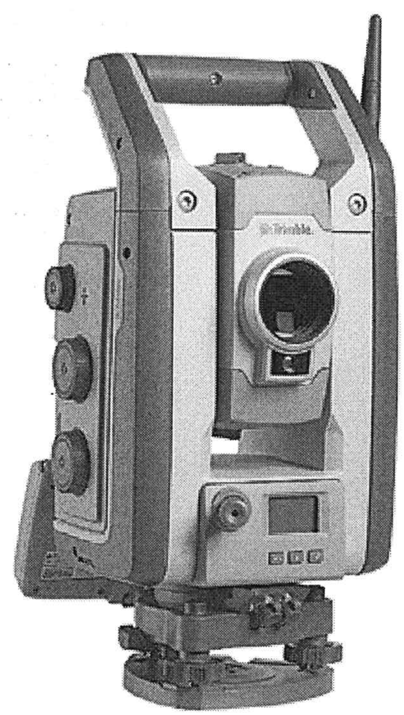
Powerful Field and Office Software

Choose from a variety of Trimble controllers operating the feature rich, intuitive Trimble Access field software. Streamlined workflows like Roads, Utilities and Pipelines guide crews through common project types, helping to get the job done faster with less distractions. Trimble Access workflows can also be customized to fit your needs.

Back in the office, trust Trimble Business Center to help you check, process and adjust your optical and GNSS data in one software solution.

Key Features

- Surveying, imaging and 3D scanning in one powerful solution
- Improved Trimble VISION technology for video robotic control, scene documentation and photogrametric measurements
- Trimble L2P real-time equipment management
- Trimble DR Plus for long range and superior accuracy
- Intuitive Trimble Access Field Software
- Trimble Business Center Office Software for quick data processing
- Seamless integration with the Trimble V10 Imaging Rover and GNSS receivers



PERFORMANCE

Angle measurement
- Sensor type: Absolute encoder with diametrical reading
- Accuracy (Standard deviation based on DIN 18723): 1" (0.3 mgon)
  2" (0.6 mgon), 3" (1.0 mgon), or 5" (1.5 mgon)
- Display (least count): 0.1" (0.01 mgon)
- Automatic level compensator
  - Type: Centered dual-axis
  - Accuracy: 0.5" (0.15 mgon)
  - Range: ±5.4' (±100 mgon)

Distance measurement
- Accuracy (ISO)
  - Prism mode
    - Standard[1]: 1 mm + 2 ppm (0.003 ft + 2 ppm)
- Accuracy (RMSE)
  - Prism mode
    - Standard: 2 mm + 2 ppm (0.0065 ft + 2 ppm)
    - Tracking: 4 mm + 2 ppm (0.013 ft + 2 ppm)
  - DR mode
    - Standard: 2 mm + 2 ppm (0.0065 ft + 2 ppm)
    - Tracking: 4 mm + 2 ppm (0.013 ft + 2 ppm)
    - Extended range: 10 mm + 2 ppm (0.033 ft + 2 ppm)
- Measuring time
  - Prism mode
    - Standard: 1.2 sec
    - Tracking: 0.4 sec
  - DR mode
    - Standard: 1–5 sec
    - Tracking: 0.4 sec
- Measurement range
  - Prism mode[5,6]
    - 1 prism: 2,500 m (8,202 ft)
    - 1 prism Long Range mode: 5,500 m (18,044 ft) (max. range)
  - Shortest possible range: 0.2 m (0.65 ft)
  - DR mode

	Good (Good visibility, low ambient light)	Normal (Normal visibility, moderate unlight, some heat shimmer)	Difficult (Haze, object in direct sunlight, turbulence)
White card (90% reflective)[3]	1,300 m (4,265 ft)	1,300 m (4,265 ft)	1,200 m (3,937 ft)
Gray card (18% reflective)[3]	600 m (1,969 ft)	600 m (1,969 ft)	550 m (1,804 ft)

    - Reflective foil 20 mm: 1,000 m (3,280 ft)
    - Shortest possible range: 1 m (3.28 ft)
  - DR Extended Range Mode
    - White Card (90% reflective)[4]: 2,200 m
- Scanning
  - Range[2,3]: from 1 m up to 250 m (3.28 ft–820 ft)
  - Speed[4]: up to 15 points/sec
  - Minimum point spacing: 10 mm (0.032 ft)
  - Standard deviation: 1.5 mm @ ≤50 m (0.0049 ft @ ≤164 ft)
    - Single 3D point accuracy: 10 mm @ ≤150 m (0.032 ft @ ≤492 ft)

EDM SPECIFICATIONS

- Light source: Pulsed Laser diode 905 nm
- Beam divergence
  - Horizontal: 2 cm/50 m (0.06 ft/164 ft)
  - Vertical: 4 cm/50 m (0.13 ft/164 ft)

Trimble S7 TOTAL STATION

SYSTEM SPECIFICATIONS

Leveling	
Circular level in tribrach	8'/2 mm (8'/0.007 ft)
Electronic 2-axis level in the LC-display with a resolution of	0.3" (0.1 mgon)
Laser class	
EDM	Laser class 1
Laser pointer coaxial (standard)	Laser class 2
Overall product laser class	Laser class 2
Servo system	
MagDrive servo technology	Integrated servo/angle sensor electromagnetic direct drive
Rotation speed	115 degrees/sec (128 gon/sec)
Rotation time Face 1 to Face 2	2.6 sec
Positioning speed 180 degrees (200 gon)	2.6 sec
Clamps and slow motions	Servo-driven, endless fine adjustment
Centering	
Centering system	Trimble 3-pin
Optical plummet	Built-in optical plummet
Magnification focusing distance	2.3×/0.5 m to infinity (1.6 ft to infinity)
Telescope	
Magnification	30×
Aperture	40 mm (1.57 in)
Field of view at 100 m (328 ft)	2.6 m at 100 m (8.5 ft at 328 ft)
Focusing distance	1.5 m (4.92 ft) to infinity
Illuminated crosshair	Variable (10 steps)
Autofocus	Standard
Camera	
Chip	Color Digital Image Sensor
Resolution	2048 x 1536 pixels
Focal length	23 mm (0.09 ft)
Depth of field	3 m to infinity (9.84 ft to infinity)
Field of view	16.5° x 12.3° (18.3 gon x 13.7 gon)
Digital zoom	4-step (1x, 2x, 4x, 8x)
Exposure	Spot, HDR, Automatic
Brightness	User-definable
Image storage	Up to 2048 x 1536 pixels
File format	JPEG
Compression ratio	User-definable
Video streaming[6]	5 frames/sec
Power supply	
Internal battery	Rechargeable Li-Ion battery 11.1 V, 5.0 Ah
Operating time[9]	
One internal battery	Approx. 6.5 hours
Three internal batteries in multi-battery adapter	Approx. 20 hours
Robotic holder with one internal battery	Approx. 13.5 hours
Operating time for video robotic[9]	
One battery	5.5 hours
Three batteries in multi-battery adapter	17 hours
Weight and dimensions	
Instrument	5.5 kg (11.57 lb)
Trimble CU controller	0.4 kg (0.88 lb)
Tribrach	0.7 kg (1.54 lb)
Internal battery	0.35 kg (0.77 lb)
Trunnion axis height	196 mm (7.71 in)
Other	
Operating temperature	–20 °C to +50 °C (–4 °F to +122 °F)
Storage temperature	–40 °C to +70 °C (–40 °F to +158 °F)
Dust and water proofing	IP65
Communication	2.4 GHz, USB, Serial, Bluetooth[9,10]
Security	Dual-layer password protection, L2P[11]

Trimble S7 TOTAL STATION

AUTOLOCK AND ROBOTIC SURVEYING

Autolock and Robotic Range[6]
- Passive prisms .... 500–700 m (1,640–2,297 ft)
- Trimble MultiTrack Target .... 800 m (2,625 ft)
- Trimble ActiveTrack 360 Target .... 500 m (1,640 ft)

Autolock pointing precision at 200 m (656 ft) (Standard deviation)[4]
- Passive prisms .... <2 mm (0.007 ft)
- Trimble MultiTrack Target .... <2 mm (0.007 ft)
- Trimble ActiveTrack 360 Target .... <2 mm (0.007 ft)

Shortest search distance .... 0.2 m (0.65 ft)

Type of radio internal/external .... 2.4 GHz frequency-hopping, spread-sprectrum radios

Search time (typical)[7] .... 2–10 sec

FINELOCK

Pointing precision at 300 m (980 ft)
- (standard deviation)[6] .... <1 mm (0.003 ft)
- Range to passive prisms (min–max)[6] .... 20 m–700 m (64 ft–2,297 ft)

Minimum spacing between prisms
- at 200 m (656 ft) .... 0.8 m (2.625 ft)

GPS SEARCH/GEOLOCK

GPS Search/GeoLock .... 360 degrees (400 gon) or defined horizontal and vertical search window

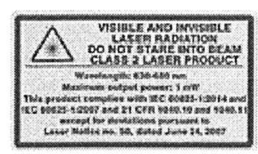
Solution acquisition time[12] .... 15–30 sec

Target re-acquisition time .... <3 sec

Range .... Autolock & Robotic range limits

1 Standard deviation according to ISO17123-4.
2 Target color, atmospheric conditions, and scanning angles will impact range.
3 Kodak Gray Card, Catalog number E1527795
4 Target shape, texture, and color; grid size, and distance and angle to target; will impact speed.
5 Standard clear. No haze. Overcast or moderate sunlight with very light heat shimmer.
6 Range and accuracy depend on atmospheric conditions, size of prisms and background radiation.
7 Dependent on selected size of search window.
8 0.5 frames per second with remote operation.
9 The capacity in −20 °C (−5 °F) is 75% of the capacity at +20 °C (68 °F).
10 Bluetooth type approvals are country specific.
11 Functionality and availability dependent on region.
12 Solution acquisition time is dependent upon solution geometry and GPS position quality

Specifications subject to change without notice.



Bluetooth®

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Appendix B – Trible R10 Product Data

Trimble R10

MODEL 2 GNSS SYSTEM

PURE, UNINTERRUPTED SURVEYING

Collect more accurate data faster and easier, no matter what the job or the environment, with the Trimble® R10 GNSS system.

Trimble 360 Receiver

Powerful Trimble 360 receiver technology in the Trimble R10 supports signals from all existing and planned GNSS constellations and augmentation systems. With the latest and most advanced Trimble GNSS technology, the Trimble R10 offers an unparalleled 672 GNSS channels to future-proof your investment.

The new Trimble R10 also provides improved interference protection to suppress a variety of intentional and unintentional sources of interference, as well as spoofing, for optimal performance in today's increasingly crowded signal frequency spectrum.

Trimble HD-GNSS Processing Engine

The advanced Trimble HD-GNSS processing engine provides markedly reduced convergence times as well as high position and precision reliability while reducing measurement occupation time. Transcending traditional fixed/float techniques, it provides a more accurate assessment of error estimates than traditional GNSS technology.

Trimble SurePoint

With Trimble SurePoint™ technology, an electronic level bubble is displayed on the Trimble controller screen, allowing surveyors to maintain focus where it matters most. Full tilt compensation allows the survey pole to be tilted up to 15° when measuring, allowing the Trimble R10 to capture points that would be inaccessible to other GNSS surveying systems.

Trimble CenterPoint RTX

Trimble CenterPoint® RTX delivers RTK level precision anywhere in the world without the use of a local base station or VRS™ network. Survey using satellite or internet delivered CenterPoint RTX correction services in areas where terrestrial based corrections are not available.

Trimble xFill

Leveraging a worldwide network of Trimble GNSS reference stations and satellite datalinks, Trimble xFill® technology seamlessly fills in for gaps in your RTK or VRS correction stream. Maintain centimeter-level accuracy beyond 5 minutes with a CenterPoint RTX subscription.

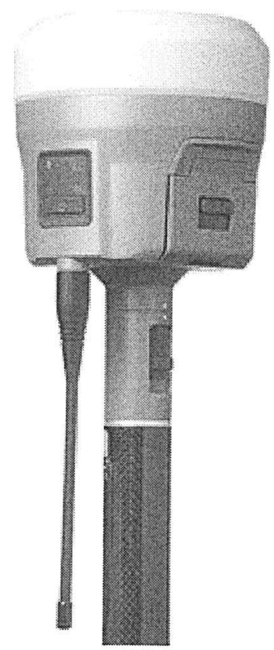
Smart, Versatile

The Trimble R10 is a versatile solution, loaded with smart features to support any workflow, all day long:

- Integrated cellular modem to receive VRS corrections or operate as a mobile hotspot
- Wi-Fi to connect to a laptop or smartphone to configure the receiver without a Trimble controller
- Bluetooth to connect to an Android or iOS mobile device running supported apps
- 6 GB internal memory to store raw observations
- Smart lithium-ion battery, with built-in battery status indicator
- Improved power management increases battery life and operating time in the field on average by 33%

Key Features

- Advanced satellite tracking with Trimble 360 receiver technology and latest generation Trimble Custom Survey GNSS ASIC with 672 GNSS channels
- Improved protection against sources of interference and spoofed signals
- Support for Android and iOS platforms
- Cutting-edge Trimble HD-GNSS processing engine
- Precise position capture and full tilt compensation with Trimble SurePoint technology
- Trimble CenterPoint RTX provides RTK level precision worldwide without the need for a base station or VRS network
- Trimble xFill technology provides centimeter-level positioning during connection outages
- Sleek ergonomic design for easier handling



PERFORMANCE SPECIFICATIONS

MEASUREMENTS		
	Measuring points sooner and faster with Trimble HD-GNSS technology	
	Increased measurement productivity and traceability with Trimble SurePoint electronic level bubble and tilt compensation	
	Worldwide centimeter-level positioning using Trimble CenterPoint RTX satellite or internet delivered correction services	
	Reduced downtime due to loss of radio signal or cellular connectivity with Trimble xFill technology	
	Advanced Trimble Custom Survey GNSS chips with 672 channels	
	Future-proof your investment with Trimble 360 GNSS tracking	
	Satellite signals tracked simultaneously	GPS: L1C/A, L2C, L2E, L5 GLONASS: L1C/A, L1P, L2C/A, L2P, L3 SBAS: L1C/A, L5 (For SBAS satellites that support L5) Galileo: E1, E5A, E5B, E5 AltBOC, E6[1] BeiDou: B1, B2, B3 QZSS: L1C/A, L1-SAIF, L1C, L2C, L5 NavIC (IRNSS): L5
	CenterPoint RTX, OmniSTAR® HP, XP, G2, VBS correction services	
	WAAS, EGNOS, GAGAN, MSAS	
	Reliable tracking in challenging environments with advanced Low Noise Amplifier (LNA) with 50 dB signal gain to reduce signal tracking effects caused by high power out-of-band transmitters	
	Additional iridium filtering above 1616 MHz allows antenna to be used as close as 20 m of iridium transmitter	
	Additional Japanese filtering below 1510 MHz allows antenna to be used as close as 100 m of Japanese LTE cell tower	
	Digital Signal Processor (DSP) techniques to detect and recover from spoofed GNSS signals	
	Advanced Receiver Autonomous Integrity Monitoring (RAIM) algorithm to detect and reject problem satellite measurements to improve position quality	
	Improved protection from erroneous ephemeris data	
	Positioning Rates	1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz

POSITIONING PERFORMANCE[2]

CODE DIFFERENTIAL GNSS POSITIONING		
	Horizontal	0.25 m + 1 ppm RMS
	Vertical	0.50 m + 1 ppm RMS
	SBAS differential positioning accuracy[3]	typically <5 m 3DRMS
STATIC GNSS SURVEYING		
High-Precision Static		
	Horizontal	3 mm + 0.1 ppm RMS
	Vertical	3.5 mm + 0.4 ppm RMS
Static and Fast Static		
	Horizontal	3 mm + 0.5 ppm RMS
	Vertical	5 mm + 0.5 ppm RMS
REAL TIME KINEMATIC SURVEYING		
Single Baseline <30 km		
	Horizontal	8 mm + 1 ppm RMS
	Vertical	15 mm + 1 ppm RMS
Network RTK[4]		
	Horizontal	8 mm + 0.5 ppm RMS
	Vertical	15 mm + 0.5 ppm RMS
RTK start-up time for specified precisions[5]		2 to 8 seconds
TRIMBLE RTX™ TECHNOLOGY (SATELLITE AND CELLULAR/INTERNET (IP))		
CenterPoint RTX[6]		
	Horizontal	2 cm RMS
	Vertical	5 cm RMS
	RTX convergence time for specified precisions - Worldwide	< 15 min
	RTX QuickStart convergence time for specified precisions	< 1 min
	RTX convergence time for specified precisions in select regions (Trimble RTX Fast Regions)	< 1 min
TRIMBLE XFILL[7]		
	Horizontal	RTK[8] + 10 mm/minute RMS
	Vertical	RTK[8] + 20 mm/minute RMS

Trimble R10 MODEL 2 GNSS SYSTEM

HARDWARE		
PHYSICAL		
Dimensions (W×H)	11.9 cm x 13.6 cm (4.6 in x 5.4 in)	
Weight	1.12 kg (2.49 lb) with internal battery, internal radio with UHF antenna, 3.57 kg (7.86 lb) items above plus range pole, controller & bracket	
Temperature[9]		
	Operating	−40 °C to +65 °C (−40 °F to +149 °F)
	Storage	−40 °C to +75 °C (−40 °F to +167 °F)
Humidity		100%, condensing
Ingress protection		IP67 dustproof, protected from temporary immersion to depth of 1 m (3.28 ft)
Shock and vibration (Tested and meets the following environmental standards)		
	Shock	Non-operating: Designed to survive a 2 m (6.6 ft) pole drop onto concrete. Operating: to 40 G, 10 msec, sawtooth
	Vibration	MIL-STD-810F, FIG.514.5C-1
ELECTRICAL		
	Power 11 to 24 V DC external power input with over-voltage protection on Port 1 and Port 2 (7-pin Lemo)	
	Rechargeable, removable 7.4 V, 3.7 Ah Lithium-ion smart battery with LED status indicators	
	Power consumption is 4.2 W in RTK rover mode with internal radio[10]	
Operating times on internal battery[11]		
	450 MHz receive only option	6.5 hours
	450 MHz receive/transmit option (0.5 W)	6.0 hours
	450 MHz receive/transmit option (2.0 W)	5.5 hours
	Cellular receive option	6.5 hours
COMMUNICATIONS AND DATA STORAGE		
Serial	3-wire serial (7-pin Lemo)	
USB v2.0	Supports data download and high speed communications	
Radio modem	Fully Integrated, sealed 450 MHz wide band receiver/transmitter with frequency range of 403 MHz to 473 MHz, support of Trimble, Pacific Crest, and SATEL radio protocols:	
	Transmit power	2 W
	Range	3–5 km typical / 10 km optimal[12]
Cellular	Integrated, 3.5 G modem, HSDPA 7.2 Mbps (download), GPRS multi-slot class 12, EDGE multi-slot class 12, Penta-band UMTS/HSDPA (WCDMA/FDD) 800/850/900/1900/2100 MHz, Quad-band EGSM 850/900/1800/1900 MHz, GSM CSD, 3GPP LTE	
Bluetooth	Fully integrated, fully sealed 2.4 GHz communications port (Bluetooth)[13]	
Wi-Fi	802.11 b,g, access point and client mode, WPA/WPA2/WEP64/WEP128 encryption	
USB v2.0	Supports data download and high speed communications	
External communication devices for corrections supported on	Serial, USB, TCP/IP and Bluetooth ports	
Data storage	6 GB internal memory; over ten years of raw observables (approx. 1.4 MB /day), based on recording every 15 seconds from an average of 14 satellites	
Data format	CMR+, CMRx, RTCM 2.1, RTCM 2.3, RTCM 3.0, RTCM 3.1, RTCM 3.2 input and output	
	24 NMEA outputs, GSOF, RT17 and RT27 outputs	
WEBUI		
	Offers simple configuration, operation, status, and data transfer	
	Accessible via Wi-Fi, Serial, USB, and Bluetooth	
SUPPORTED CONTROLLERS		
	Trimble TSC7, Trimble T10, Trimble TSC3, Trimble Slate, Trimble CU, Trimble Tablet Rugged PC, Android and iOS devices running supported apps	
CERTIFICATIONS		
	FCC Part 15 (Class B device), 24, 32; CE Mark; RCM; PTCRB; BT SIG	

Trimble R10 MODEL 2 GNSS SYSTEM

1 The current capability in the receivers is based on publicly available information. As such, Trimble cannot guarantee that these receivers will be fully compatible with a future generation of Galileo satellites or signals.
2 Precision and reliability may be subject to anomalies due to multipath, obstructions, satellite geometry, and atmospheric conditions. The specifications stated recommend the use of stable mounts in an open sky view, EMI and multipath clean environment, optimal GNSS constellation configurations, along with the use of survey practices that are generally accepted for performing the highest-order surveys for the applicable application including occupation times appropriate for baseline length. Baselines longer than 30 km require precise ephemeris and occupations up to 24 hours may be required to achieve the high precision static specification.
3 Depends on WAAS/EGNOS system performance.
4 Network RTK PPM values are referenced to the closest physical base station.
5 May be affected by atmospheric conditions, signal multipath, obstructions and satellite geometry. Initialization reliability is continuously monitored to ensure highest quality.
6 RMS performance based on repeatable in field measurements. Achievable accuracy and initialization time may vary based on type and capability of receiver and antenna, user's geographic location and atmospheric activity, scintillation levels, GNSS constellation health and availability and level of multipath including obstructions such as large trees and buildings.
7 Accuracies are dependent on GNSS satellite availability. xFill positioning without a Trimble CenterPoint RTX subscription ends after 5 minutes of radio downtime. xFill positioning with a CenterPoint RTX subscription will continue beyond 5 minutes providing the Trimble RTX solution has converged, with typical precisions not exceeding 6 cm horizontal, 14 cm vertical or 3 cm horizontal, 7 cm vertical in Trimble RTX Fast regions. xFill is not available in all regions, check with your local sales representative for more information.
8 RTK refers to the last reported precision before the correction source was lost and xFill started.
9 Receiver will operate normally to −40 °C, internal batteries are rated to −20 °C.
10 Tracking GPS, GLONASS and SBAS satellites.
11 Varies with temperature and wireless data rate. When using a receiver and internal radio in the transmit mode, it is recommended that an external 6 Ah or higher battery is used.
12 Varies with terrain and operating conditions.
13 Bluetooth type approvals are country specific.

Specifications subject to change without notice.

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