



Leica Absolute Tracker AT401  
White Paper

*Leica*  
Geosystems



 **HEXAGON**  
METROLOGY

## Abstract

This white paper presents the bridge between traditional laser Trackers and modern tracking Total Stations. It will detail how the individual pieces from these two products combine to create the world's first ultra large scale truly portable CMM. A laser tracker that is able to be powered by its own internal battery and is able to work in the most demanding environment, yet maintains the highest level of precision and the largest ever work envelope. An "All in One" system design combined with an all new telescope concept deliver the groundwork for the next generation Absolute Tracker, the Leica AT401.

## Introduction

Laser Trackers have been the benchmark tool for large scale high accuracy alignment and inspection tasks for the last two decades. 20 years ago Leica Geosystems introduced the world to the SMART 310. This first laser tracker was capable of measuring to  $\pm 10\mu\text{m}$  per meter over a range of 25 meters. Although it was incredibly accurate, it wasn't exactly portable. It required a tracker processor and a controller box (essentially two additional large computers) in addition to the running application PC. The system required mains power for operation and had a 30 minute warm-up period before the operator could start to take measurements.

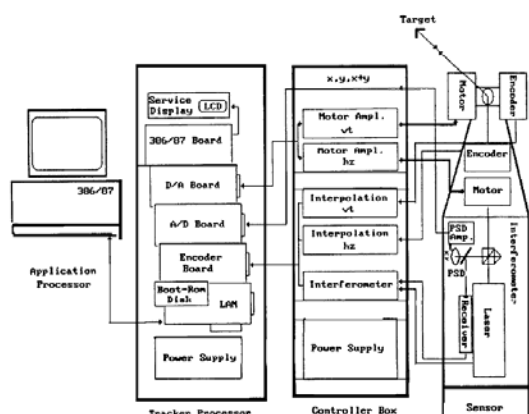


Figure 1– Block diagram of a Leica Smart 310 Laser Tracker

Laser Tracker technology has grown substantially over the last 20 years. Trackers today have become smaller, lighter more portable and easier to use but they still have some key limitations that prevent them from being used in all industries. All standard laser trackers require mains power, meaning that you have to be within an acceptable range to a building with AC power to be able to use them. The second problem is that most systems have been designed for indoor use and have ventilation ports on either the sensor head or the controller that prevent them from being used in demanding outdoor environments without additional protection. Because most standard laser trackers have been designed for indoor use, the measurement range is quite limited. Some laser trackers only have a radial range of 15 m which limits the size of the object that can be accurately measured.

On a similar time line the tracking total station was starting to emerge in the surveying world. This was a total station that could follow a moving reflector allowing an operator to measure by themselves. In the mid 1990's Leica Geosystems released the TDA5000. This was their first high accuracy tracking total station. It introduced an all new Automatic Target Recognition (ATR) technology that allowed the total station to automatically target a reflector and track it while moving. These sensors were battery powered and sealed for use in the most demanding environments (including rain), but in even the best conditions were only accurate to around 0.25 mm, factors away from the 40 to 50 micron tolerance required by laser tracker applications.

While laser trackers were getting smaller and lighter, tracking total stations were becoming faster and more functional. In 2009 Leica Geosystems introduced the TDRA6000 laser station. This new sensor utilized Leica Geosystems' fourth

generation ATR technology that provided frame rates factors faster than previous sensors. The speed of this new ATR was combined with a high-speed quadruple detection angle reading system and all new proprietary Piezo direct drives that allowed high speed tracking applications to become a reality. The TDRA6000 was the first metrology based total station to have the speed and dynamics approaching a traditional laser tracker, but its accuracy was still factors less than required.

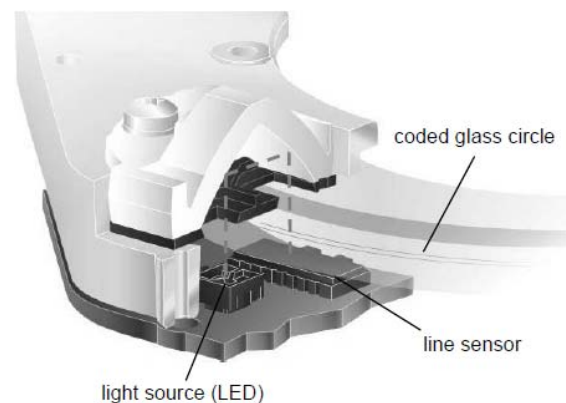
### ***The Alidade***

The lower stand assembly (alidade) includes everything except the telescope. The design and development of this structure exemplifies the depth of Leica Geosystems and Hexagon Metrology. Components of this alidade are shared between the TS30 Surveying platform, the TPS6000 Metrology platform and now the AT401 laser tracker. All of these sensors share the same 0.5 arc second angular encoders, the same precision level to gravity sensor and the same advanced Piezo drive technology. Although the individual design criteria are different, all of these sensors share the same need for an extremely sturdy alidade. In order to guarantee 0.5" accuracy under very demanding conditions (changing temperatures, wind, rain, etc...) a new design and manufacturing process was required compared to standard total stations.

The Alidade for these sensors was designed with all of these parameters in mind and utilizes a low pressure casting technology. This "gravity fed" casting process is slower and more costly than standard die-casting technology that is common in modern total stations, but is the only way to achieve the temperature stability and stiffness that is required by these ultra high accuracy sensors.

### ***The Angle Measurement System***

The angle measurement system is a very significant component for the products based on this common alidade. The angle encoders must guarantee highly precise and accurate angle measurements, and must do so even under the high speed of the Piezo direct drives. The quadruple reading angle measurement system consists mainly of a coded glass circle and four encoders. Each encoder has an LED light source, mirrors for reflecting the emitted light, and a digital line sensor. The coded glass circle is based on radially aligned lines and is absolute and continuous. No initialization of the angle sensor is required prior to being able to measure. Figure 2 shows a 3D-illustration of an exemplary single encoder and the coded glass circle of the angle measurement system.



***Figure 2 – Single encoder of the angle measurement system with a light source (LED) and a line sensor.***

For the angle measurements, a light emitted by the LED is projected through the coded glass circle and onto the line sensor. In order for the image from the line sensor to be transformed into relative angle information, it must first be decoded. A first coarse angle is detected with an accuracy of about 0.3 gon based on the individual coded lines. The precise angle measurement is calculated from the position of the coded lines' centroid with algorithms developed by Leica Geosystems. For a position determination, at least 10 code lines have

to be captured by the line sensor. To increase the interpolation quality of the actual position, a minimum of 30 code lines are used for the signal processing.

Not only is this process very fast (with measurement frequency of up to 5000 angle measurements per second), but it is also incredibly accurate because the actual position of the coded glass circle is detected by four individual encoders. This allows systematic and periodical errors to be eliminated increasing the measurement accuracy while the additional overall number of angle measurements increases the reliability. By using two encoders for the angle measurements, the periodic error of the eccentricity of the coded glass circle compared to its rotational axis is eliminated. The additional two encoders (for a total of four) remove further minor -periodic errors and according to the variance propagation equation (cf. Equation 1), improve the measurement accuracy by a factor of about 0.7 to an overall  $1\sigma$  accuracy of 0.15mgon (0.5") according to ISO 17123-3.

$$\sigma_{4encoders} = \frac{1}{\sqrt{2}} \sigma_{2encoders} \quad (1)$$

### Precision Level to Gravity Sensor

The dual axis inclination sensor monitors the horizon of the alidade. In the ideal case, the horizon of the instrument would always be perpendicular to the plumb-line or gravity vector. However, in the real world this isn't actually possible so the inclination sensor detects and corrects the actual deviations between the two. Figure 3 shows the principle of the dual axis inclination sensor which is implemented in the AT401.

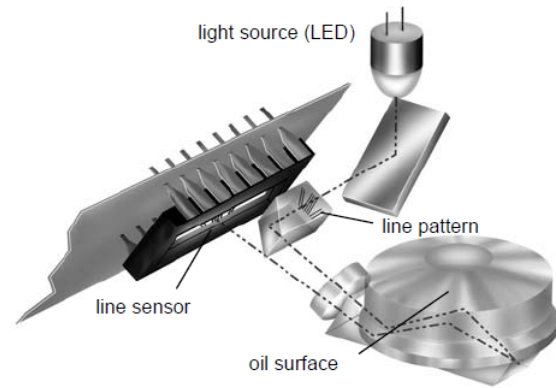


Figure 3 – Principle of the dual axis inclination sensor.

The inclination sensor mainly consists of an oil layer in a casing together with a prism that has an integrated line pattern, a digital line sensor, a light source and mirrors for reflecting the emitted light. The line pattern is projected on the line sensor after passing through the oil layer and being reflected twice by its surface. The specific triangular line pattern allows the detection of both transverse and longitudinal inclination components by means of a one dimensional receiver (cf. Figure 4).

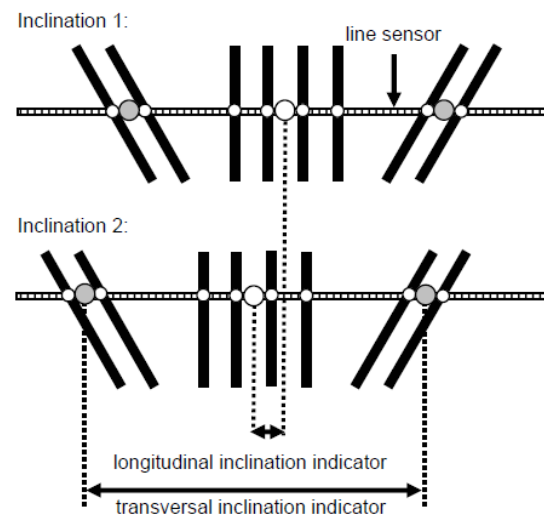


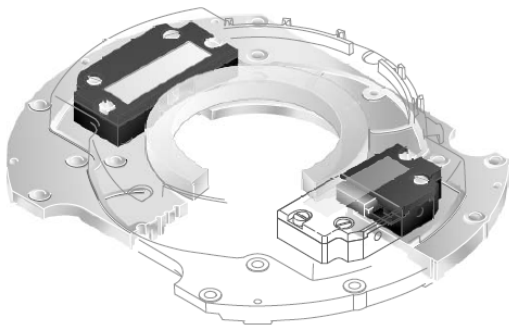
Figure 4 – Line pattern for measuring longitudinal and transversal inclination by a one-dimensional line sensor.

For transversal inclinations, the spacing between the diagonal lines is altered. For longitudinal inclinations, the center of the entire line pattern is shifted along the line sensor. This concept enables a very small construction size which allows the dual axis inclination sensor to be positioned in the center of the standing

axis of the alidade. By doing so, the liquid surface displacement is minimized from its horizontal position while rotating the alidade. This minimizes the settling time for the oil layer and allows instant measurements after a rotation, which in turn, allows the compensator to be used to correct every measurement, not just a single gravity vector measurement.

### ***Piezo Direct Drives***

These exciting new drives are based on the Piezo electric principle, which directly transforms electric power into mechanical movements. These drives incorporate maximum speed and acceleration together with nanometer level positioning and very low power consumption.



*Figure 5 – Direct drive of the Leica AT401.*

Each drive consists of a pair of diametrically mounted piezo-electric ceramics that accelerate and precisely position a ceramic cylindrical ring which is attached to the axis of the alidade (cf. Figure 5). The mounted piezo-electric ceramics are polarized and divided into an active and a passive electrode. A ceramic nose transfers the movements of the mounted piezo-electric ceramics to the ceramic ring. The nose moves in an elliptical pattern pushing against the ceramic ring at its tangent causing the mounted piezo-electric ceramics to spin around the fixed ring. The direction and the speed of the elliptical movements are controlled by the particular active segment of the mounted piezo-electric

and the strength of the alternating voltage.

The power consumption of the drives for this shared alidade was a crucial design factor. Less power consumption, specifically when at rest, significantly extends the operating time of the batteries. An advantage of the Piezo direct drives is that they only need power when in motion. They are able to hold the horizontal and vertical positions of the alidade and telescope without using any power. This saves energy, does not produce any uncontrolled heat and enables stable measurements over longer periods of time. The actual horizontal and vertical positions of the alidade and telescope are clutched very stable, but are not fixed. This enables the sensor to be aimed by hand without disabling or constantly turning on and off the motors.

### ***Absolute Distance Meter***

Although the alidade is shared between many sensors, the telescope of the AT401 is a completely new design. One of the most important criteria for this telescope was an incredibly accurate electronic distance meter (EDM). Most total stations use either Time of Flight or Phase based EDM's. Each of these technologies has its own strengths and weakness, with trade offs between speed and accuracy. Even when these limitations are minimized, as is done in the unique System Analyzer technology that exists in the TDRA6000, this technology is simply not capable of accuracies better than tenths of millimeter. To reach into the hundredths of millimeters it was necessary to turn to laser tracker technology for this new EDM. The first EDM was put into a laser tracker in 1995 when Leica Geosystems first introduced the LTD500. At that time the term Absolute Distance Meter (ADM) was introduced. An ADM differed from an EDM only by the level of accuracy that it

was capable of delivering. While most common EDM's were accurate to within a couple of millimeters, the Leica ADM was accurate to a couple of hundredths of a millimeter.

The technology for the first Leica ADM originally came from the Kern Mekometer 5000 or ME5000. The ME5000 was used to measure distances up to 8 kilometers (5 miles) with a typical accuracy of 0.2 mm + 0.2 ppm. It was the most accurate long range electronic distance meter of its time, and is still in use today for high accuracy engineering surveys. Both the original ME5000 and the LTD500 ADM used the same unique patented Polarization Modulation principal that's very insensitive to both long distances, and environmental influence.

This principal is based on the "electronified" cogwheel discovered by A.H. Fizeau in 1849, and uses frequencies rather than a fixed reference length to determine the measured distance. As the cogwheel rotates, the bits of light are sent out and reflected back by a retro reflector. The intensity of the reflected light changes with respect to distance as the speed of the cog-wheel changes. H.A. Fizeau was able to observe a first minimum intensity in a test utilizing a cogwheel with 720 cogs, a rotation speed of 12.6 revolutions per second and a known distance of 8.6km. From this he determined that the speed of light to be 313000 km/Sec (cf. Figure 6)

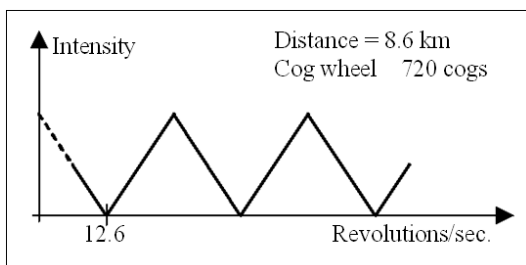


Figure 6 – The principals of Fizeau's first cogwheel experiment.

Today it's known that the actual speed of light (in a vacuum) is 299793 km/Sec. Fizeau's inaccuracy was primarily due to

the inaccuracy in his original cogwheel speed determination. Had he been able to determine the speed of the cogwheel more accurately, his results would have been almost perfect.

To control this more accurately in the ME5000 and LTD500 ADM an alternating current was applied to a crystal to create the frequencies that were originally generated by Fizeau's cogwheel (cf. Figure 7). This "electronified" cogwheel used a roughly 900 MHz modulation frequency and was able to achieve a 1µm resolution.

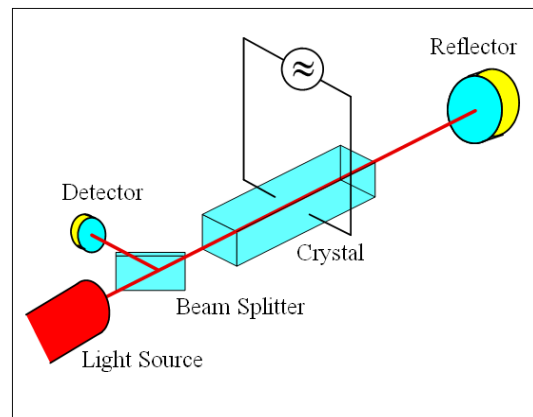


Figure 7 – The "electronified" cogwheel of the Leica LTD500 ADM.

The other two key parameters (in addition to the modulation frequency) are the frequency bandwidth and synthesizer (frequency) resolution. These three parameters influence both the achievable accuracy and the shortest measurement distance. The original Mekometer had a maximum modulation frequency of 510MHz, with a frequency bandwidth of 20MHz. The smaller the frequency bandwidth the longer the required minimum measurement distance, with the Mekometer requiring a minimum measurement distance of about 20 meters. To make this technology more functional in the ADM in the LTD500 laser tracker, the maximum modulation frequency was increased from 510MHz to 900MHz, increasing the frequency bandwidth to 150MHz. Increasing these parameters is the equivalent of using a

better scale to measure with; the higher the modulation frequency and the smaller the synthesizer resolution, the more accurate the achievable result is.

To increase this even further the maximum modulation frequency of the ADM in the AT401 was increased to 2.4GHz providing a frequency bandwidth of 300 MHz. This increase in frequency, in addition to an improved high speed synthesizer design which allows for higher resolution of the frequency steps, give this new design a typical accuracy over an 80m range of +/- 5µm.

Creating a test procedure to certify a distance meter to this accuracy was quite difficult. There are not many devices that can measure significantly more accurate than this to establish a base line, so the engineers were forced to use the device to certify itself. The advantage to this style of distancing technology is that the accuracy of the frequencies determines the accuracy of the distance. This means that a long base line is not needed. The frequencies of the synthesizer are verified against a traceable frequency counter to determine the scale of the ADM (typically around 0.1ppm). The sensor then measures set points over 80 meters multiple times to verify that the ADM is repeating within the +/-5µm MPE specifications.

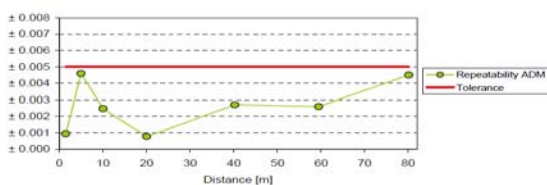


Figure 8 – Leica AT401 80 meter ADM repeatability check.

Figure 8 above shows a single system report from the production end check that each system must pass before leaving the factory. The second ADM check that is done is to prove the

absolute accuracy of the distance module. In the test above, the ADM could be very repeatable, but have large shifts in the absolute accuracy that would not be detected. So in the second test three poles are set roughly 20 meters apart and are measured respectively from 3 separate stations. Station #1 is inline with the three poles but outside. Station #2 is inline with the poles and between poles 1 and 2. Station #3 is inline and between poles 2 and 3. This guarantees that the relative distances measured between the poles is always the same between sensor positions. Through standard error propagation of the measurement of two points a tolerance of +/- 14µm was established. Figure 9 is from the same sensor as repeatability test, but showing the results of the absolute measurements.

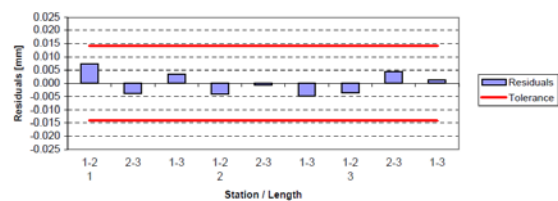


Figure 9 – Leica AT401 ADM absolute distance check.

### ATR & Laser Pointer

All modern tracking total stations have an eyepiece that allows the operator to manually sight an object through the telescope. This is because most surveying sensors are used for multiple purposes; tracking is only one of them. The AT401 on the other hand was designed from the ground up with one task in mind – tracking. Therefore the eyepiece of the telescope was removed to be able to utilize a more advanced triple beam design.

The first beam is a simple laser pointer that is used as a visual aid so that the operator who is moving the reflector can see where the sensor is pointing. This is a visible red beam from a laser diode operating in the 635nm wavelength. It

has a Gaussian beam pattern that allows the narrowest point to be set away from the system (cf. Figure 10)

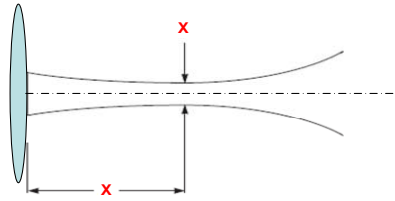


Figure 10 – Typical Gaussian beam profile.

In a standard laser tracker this Gaussian beam is also used to determine the angular position to the reflector. The laser beam is emitted from the laser tracker and reflected back onto a Position Sensing Detector (PSD). The PSD is integrated into a control loop with the angle encoders and motors to keep the beam on the reflector as it moves. As the reflector starts to move in a given direction the beam will move from its original position on the PSD. This movement is communicated to the drive system (both encoders and motors) to position the beam back to the center of the PSD. With a Gaussian beam as shown in Figure 10 the further away the reflector is from the narrowest point or "beam waist", the less "focused" the beam is. As the beam becomes more divergent less light falls onto the reflector and less light is therefore returned to the PSD. This is the limiting factor in most standard laser trackers. The sensor stops measuring at further distances because the PSD can no longer detect the reflector. The Telescope in the AT401 doesn't use a PSD at all. Instead the visible beam is just used as an operator aid for pointing while all of the positioning is done by the Automatic Target Recognition system.

As mentioned earlier, Leica Geosystems has had some form of Automatic Target Recognition built into their sensors for more than 15 years. Rather than using a PSD, the ATR uses a Complementary Metal-Oxide-Semiconductor (CMOS) sensor. An infrared beam is transmitted coaxially with the telescope line of sight towards a reflector that is in the Field of

View (FOV). The beam is then reflected back creating an image on the CMOS chip. The CMOS chip replaces the PSD in the control loop allowing the reflectors delta position to be communicated to the drive system so that the AT401 can constantly track the reflector.

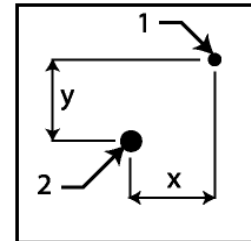
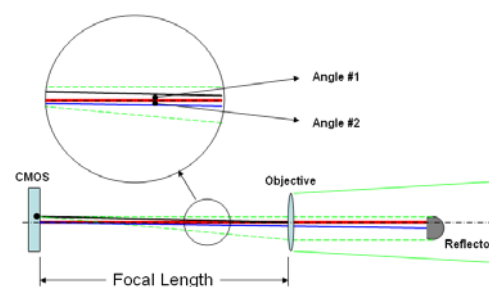


Figure 11 – 2D image coordinates of the ATR CMOS.

The CMOS image information is linked to the reflector angular location by help of the borehole geometry (cf Figure 12). This can be simplified as follows:

- Line of Sight – A straight line through the center of both the objective and the CMOS chip (dotted line)
- Line of Object – A straight line connecting both the center of the object and the center of the CMOS chip (blue line)
- Line of Image – A straight line connecting both the center of the objective and the center of the image on the CMOS chip (black line)

The angle between line of sight and line of object (angle #1) equals the angle between the line of sight and line of image (angle #2). These angles can be calculated from the known image pixel position on the CMOS array (cf. Figure 11), the focal length and the size of the pixel.



12 – ATR borehole geometry.

Figure



Coherent light sources, e.g. laser diodes, tend to have a non-homogeneous light distribution characterized by "hot spots" or bright points within the beam. As consequence at the farther distances the CMOS array only detects a very small dot of light from the reflector, but in the near range almost the entire CMOS array is filled with light. In this case a bright spot in the image can make the reflector position appear different than it actually is.

The AT401 on the other hand, uses a Superluminiscent LED (SLED) as the ATR light source. Whereas a Laser Diode emits a narrow bandwidth, a superluminiscent diode emits a broader spectrum of wavelengths, in the case of the AT401 ATR typically about 20nm (3dB). This removes any intensity issues or "hot spots" in the short range.

In order for a traditional laser tracker to lock-on to a reflector the reflector must be in line with the visible laser beam (+/- a couple of millimeters) in order for the beam to be returned back to the PSD. With the ATR concept, the reflector only needs to be somewhere within the 0.6° FOV of the ATR. Figure 13 represents a standard reflector 5 meters away from the AT401 with the green circle representing the FOV of the ATR. As long as the center of the reflector is anywhere within this green circle the ATR can lock-on and track its position. Figure 14 represents a standard reflector 5 meters away from a normal PSD laser tracker. The green circle represents the equivalent "field of view" of the PSD. The center of the reflector must be positioned within this green circle for the PSD to be able to lock-on and track the reflector.

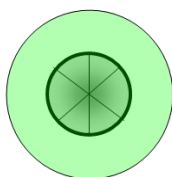


Figure 13 – ATR FOV.



Figure 14 – PSD FOV.

The further away from the AT401 the larger this green circle becomes. In comparison the green circle of the standard laser tracker stays roughly the same size over the entire measurement range. This gives the AT401 the ability to deal with much higher dynamic movements when compared to a traditional laser tracker.

With this large of a FOV it is possible that there can be multiple reflectors seen by the sensor at one time. Therefore special algorithms were generated to determine which reflector is the correct reflector when more than 1 option is available. This also helps to detect measurement reflectors from "other" reflections in the work environment. These algorithms work in combination with a series of special band path optical filters and a unique differential imaging process to guarantee that the correct reflector is always selected.

### ***OVC & PowerLock***

Leica laser trackers have had the capability to use overview cameras (OVC) since the LTD500 introduction in 1995. In the LTD500 the OVC provided the operator with the ability to visually see any reflectors that the laser tracker could measure directly on the PC screen. This allowed the LTD500 Laser Tracker to be used in heavily automated systems where the operator may not have been able to control the direction of the tracker but still needed to manually reposition the laser beam. For these tasks the operator could simply open the live video stream and click the mouse pointer in the video image where the sensor should be positioned. If the desired position was outside of the FOV of the OVC then the operator could steer the horizontal and vertical positioning of the sensor using the arrow keys on the keyboard while watching the live video stream to see where the sensor was pointing. In the LTD500 integration the OVC used the

same steering mirror as the laser beam. This meant that while the OVC was showing a video image the laser tracker was unable to measure. Once the operator clicked on the reflector that needed to be measured the mirror would switch back to the laser beam so that the sensor could then complete the measurement. In the AT401 the OVC can now also be used as a live video source while the sensor is measuring. The camera provides a 10° FOV and illuminates any targets within this view with a blinking IR light source. There are times when an operator may want to control this behavior manually (by clicking in the image of the PC), and there are times when the operator may want this process to be automated, this is where PowerLock comes in.

PowerLock was first introduced by Leica Geosystems in the AT901 Absolute Tracker. It allowed the system to detect when a reflector was in view of the tracker and automatically lock onto it. This is particularly useful since the AT901 uses a standard PSD and prior to the introduction of PowerLock had the same limitations as all other PSD laser trackers described earlier. With the AT401 the FOV of the PowerLock module has been expanded to match the 10° FOV of the OVC. The PowerLock CMOS sits right next to the OVC CMOS in the telescope but has a completely separate design. The OVC is designed for live video and produces 30 frames per second of VGA quality video. The OVC has been designed to allow the user to see what the sensor has line of sight to. The PowerLock module on the other hand uses slightly less resolution but a much higher frame rate of up to 200 frames per second. This ultra fast update rate allows the AT401 to track a moving reflector using just the PowerLock module. The optics for the PowerLock vision tracking system have been designed to only allow a narrow band pass of light to reach the CMOS. This band pass is matched to the

output frequency of the IR diodes that illuminate the reflector. By combining this with Leica Geosystems' specific algorithms for differential imaging, the PowerLock module has the ability to distinguish between reflectors that can be measured and stray reflections in the work place.

### ***Superior Tracking performance***

In order for a laser tracker to track a target accurately it must deal with very high acceleration rates. It is not the speed at which the reflector is moving but the very fast change in direction that occur during hand held use that can cause problems. Simply looking at the acceleration rate of the drives in a tracking device will only give you a portion of how well the device will actually track a reflector. The other factor is how "fixed" the beam of the laser tracker must stay relative to the reflector. This can be explained with Figures 13 and 14 on the last page. The center of the reflector can move anywhere within the green circle and the tracker can still see it. Once the reflector falls outside of that area the tracker can no longer track the reflector. As a reflector moves through space, the control loop of the tracker is constantly calculating where the reflector is and adjusting the drives to keep the laser beam (or the virtual green circle) in the center of the reflector. The larger this area is the better the tracker can react to dynamic changes in direction. This gives the control loop more time to correct the laser beam position before the reflector has moved so far that it can no longer calculate its next position.

The AT401, however, works on a completely different principal. Not only is the virtual green circle bigger than with a standard laser tracker, but it continues to grow the further away from the sensor the reflector is. At a distance of 60 meters the field of view of the ATR (tracking sensor) is more than half a

meter as compared to a field of view of only a few (millimeters for a standard tracker). In addition to this, the AT401 can also use the PowerLock module to track the reflector. This gives the sensor an effective field of view of more than 1m x 1m at a distance of only 6 meters. Figure 15 shows the full field of view of the PowerLock module at only 1.5 meters.

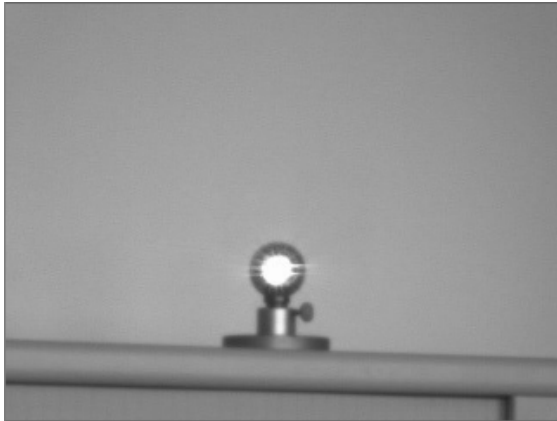


Figure 15 – Leica AT401 PowerLock FOV at 1.5 m.

Anywhere that the reflector moves inside this image the sensor can track accordingly. This means that even if the reflector passes behind objects that are in the path of the laser beam the AT401 can continue to track them. This does however create a new condition, where the AT401 is tracking a reflector, but it is not yet ready to measure.

Traditionally laser trackers have had two states, locked-on (tracking) and ready to measure, or not locked-on. The AT401 introduces a new state, locked-on (tracking) not ready to measure. Even though the reflector can be tracked through the full 10° FOV of the PowerLock module, the ADM beam isn't always on the reflector. This means that at times the sensor will be tracking the reflector but the system will be unable to measure because it doesn't have a valid distance.

When the sensor is locked onto a stable target the system will be "ready to measure" as indicated by a solid green LED on the sensor. If the reflector is moving then the system will be "locked

on" but not "ready to measure". This is indicated by a blinking red LED on the sensor. If the reflector is completely out of the field of view, then the sensor LED will be solid red indicating that no reflector can be detected. At this time the blue LED should also be illuminated indicating that PowerLock is enabled. As soon as a reflector is presented within this 10° FOV, the system will automatically try to regain lock. If the reflector isn't moving too fast then the LED will return to solid green indicating that a measurement can be started.

### ***Static vs. Dynamic Measurements & Accuracy***

The technology combination in the AT401 provides the greatest ease of use due to the best tracking performance. However, even though the AT401 can dynamically track a reflector better than any traditional laser tracker, there is still no match to an actual AIFM for dynamic measurements. Even the fastest ADM can not match a Laser Interferometer for fast dynamics. All absolute distance meters must deal with integration times (the time required to perform the operations that determine the target's position). Integration time is similar to the shutter speed on a camera, the longer the exposure time, the harder it is to take a clear picture of a fast moving object. The same is true with integration, the longer the integration time, the more likely you are to introduce an error in the measurement of a moving object. If an ADM is able to measure at 10,000 measurements per second, then it has a 100 microsecond integration time. If the reflector is moving during this time, then any movement during the integration has the potential to be applied to the uncertainty of the measurement. For example, if a reflector is moving at a 1/2 meter per second during integration, and if an ADM with a 100 microsecond integration time is used to measure it, then the uncertainty during integration =

0.05 mm. The uncertainty of the measurement could be as bad as the uncertainty of the ADM (10 $\mu$ m) plus the uncertainty due to the movement (50 $\mu$ m), making the total measurement uncertainty up to 60 $\mu$ m, or if standard error propagation is taken into account then about 51  $\mu$ m.

Because of these uncontrolled errors some ADM only trackers are viewed as less accurate than traditional laser trackers that use both an ADM and an Interferometer in combination. Since the introduction of the LTD500 laser tracker in 1995 Leica Geosystems have proven that our core ADM design is incredibly accurate for static point measurement. This is how all of the Leica laser trackers have worked for the last 15 years. Prior to the introduction of the AIFM, if the laser beam was interrupted then the operator would "catch" the beam with the reflector and have to place it in a stable location in order for the sensor to be able to lock back on. In this process the ADM would set a new valid distance to the Interferometer (IFM), and the IFM would start measuring dynamically from this new known starting point. With the LTD500 this process took between 2 – 3 seconds, and then the sensor was ready to measure dynamically again.

The AT401 works similarly, but significantly faster. If the beam is interrupted the PowerLock module will automatically lock back onto the reflector. If the reflector is moving the ADM will measure a distance so that the sensor can return a 3D coordinate, but due to the inaccuracies described earlier, these coordinates can not be used as an actual measurement, they are just used to update the on-line reflector position in the standard metrology applications. A measurement can only be triggered once the reflector is stable enough to guarantee that the result is accurate. This maintains that even as an ADM only device the AT401 can maintain the same

accuracies as the AT901 with its advanced AIFM dynamic distancing unit.

One of the best ways to verify this accuracy is with a large volume network measurement. A test network was established that measured 15 meters long by 7 meters wide by 5 meters tall. 27 points were distributed to best utilize the geometry of the space. These points were then measured with a Leica AT401 from 3 evenly distributed locations within the volume (cf. Figure 16).

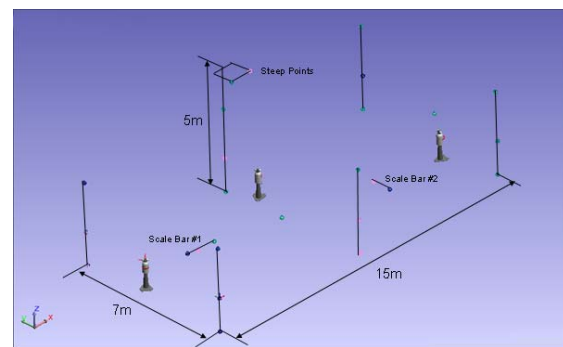


Figure 16 – Leica AT401 3D network setup.

All 81 observations were then processed using a bundle adjustment to create a nominal point set. Each individual station was then compared back to the bundled nominal point set using a 3 – 2 – 1 alignment. Figure 17 shows both the standard deviations and the maximum deviations of the station comparisons.

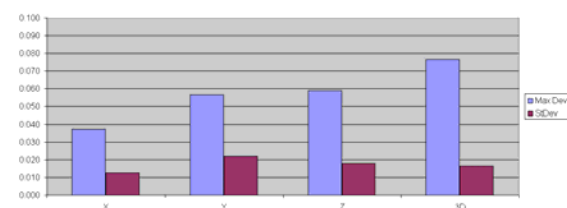


Figure 17 – Leica AT401 3D network results.

The 6 points that were set at the horizon in the network were also evaluated to determine how accurately the sensor performed "level to gravity". These were processed from each station separately zeroing out the height at the same location. With different station orientations at each location the

residuals never exceeded +/- 50µm over the full 15 meter volume.

### **Completely Wireless Design**

To satisfy the wireless design criteria three things had to be taken into account.

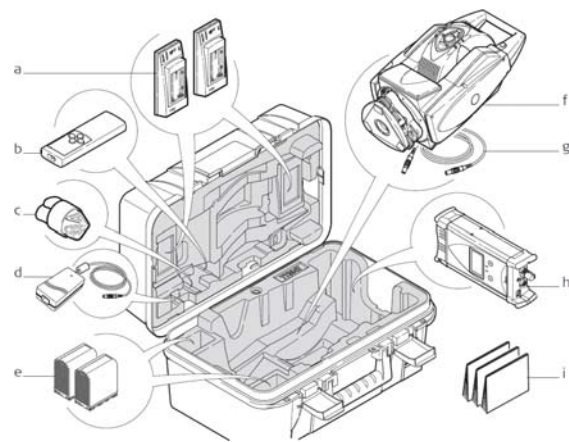
- How to communicate to the sensor
- How to control the sensor
- How to power the sensor

A number of wireless standards exist, from engineering level solutions, to more mainstream solutions like Bluetooth and WiFi. All of these standards were taken into consideration but finally the WiFi standard was chosen. WiFi provides excellent scalability with a huge industry install base. It offers high speeds, easy setup and is a widely used international standard.

Controlling the sensor became the next question. It is of course possible to use the Application Software on the computer to trigger measurements, but how does someone 20 meters away from the computer work it? There are many off the shelf solutions to remotely control a standard PC application but many require an additional radio band that is often forbidden in the factory work environment. The units that use infrared bypass this limitation, but require line of sight to the receiver, and this isn't always possible. To eliminate this problem the AT401 has a built in IR receiver and bundled IR transmitter remote control. The IR receiver is located near the objective lens in the telescope, since the sensor will always have line of sight to the reflector, then the operator should always have line of sight back to the telescope (similar to the IR communication of the Leica T-Probe). This very simple IR remote allows any measurement application the ability to process the button presses as they see fit, or even allow the user to assign them accordingly.

### **Advanced Power Management**

The last hurdle in making the sensor completely wireless is dealing with how to power it. Since all of the main modules in the AT401 were designed with low power consumption in mind the ability for the system to run for extended periods on battery power seems quite logical. The AT401 has two identical Lithium Ion batteries, one in the sensor and one in the controller. With both batteries fully charged the sensor will run for well over half a day. The battery in the sensor has first priority meaning that it will discharge first. As soon as this battery is empty the battery in the controller will take over (without interruption). Once the sensor battery is dead and the controller battery reaches a critical level the operator has two choices. They can either replace the battery in the sensor with a freshly charged unit, or they can hot swap the controller battery without interruption. Either way the AT401 will continue running as if nothing ever happened.



*Figure 18 – Leica AT401 "All in One" case design.*

The sensor case (cf. Figure 18) includes room to store two additional batteries (e) as well as a dual plate battery charger (a) that is capable of charging two batteries sequentially. The battery charger can be run off of either the included mains (AC) power supply (d) or a 12V DC car adapter that plugs into the cigarette lighter of most automobiles. If it is preferred to

power the system from AC power, the same AC power supply that is used to power the battery charging plates can be plugged directly into the controller (h). In this configuration the internal batteries are not used, and instead the system draws all of its power from the AC mains. If however there would be a power interrupt and the sensor had charged batteries in it, it would automatically switch over to battery power without interruption. If the sensor is always going to be powered from AC mains as would be the case in a fixed or Metrology Automated Assembly (MAA) installation, it can also be powered directly from the RJ45 LAN port using Power Over Ethernet technology.

Power Over Ethernet or "PoE" was originally designed as a low power protocol for devices like conference phones and web cameras.

It has since grown into a higher power PoE<sup>+</sup> standard that can drive 60 – 90 watt devices.

The AT401 has an optional module to take advantage of this exciting new technology. By simply replacing the controller battery with the PoE<sup>+</sup> module the sensor can be powered directly from the RJ45 LAN port. This allows a single off the shelf Cat5 LAN (TCP/IP) cable to run both power and data to the sensor. This configuration uses a power injector or "midspan" to insert power into the Cat5 cable. The AT401 PoE module then separates this power from the data automatically making it the easiest sensor ever developed for fixed installations.

### ***Summary – Benefits of the Absolute Tracker AT401***

#### ***Complete Portability and Durability –***

The complete measurement system weighs less than 15 kilo (including the case). Using a common design from a surveying theodolite, but integrating

state of art laser tracker technologies provides the smallest most portable long range laser tracker ever produced.

#### ***Ready for Any Environment –***

The whole system is IP54 rated for use in the most demanding environments. There are no internal cooling fans to disturb the sensor or the controller. Both the sensor and controller are completely protected from both dust and water.

#### ***Advanced Power Management –***

By utilizing lower power consumption design criteria, the AT401 has more power options than ever before thought possible. It can be powered by its own internal battery, by AC mains power, or even by the unique PoE<sup>+</sup> module that allows for both power and data to be transferred over standard Cat5 Lan cables.

#### ***Completely Wireless Design –***

By integrating a standard wireless communication module every AT401 can be run without requiring cables. Driven by internal batteries and using a WiFi data link the station can be remotely setup without the operator having to worry about power and data lines.

#### ***Ultra Large Volume Measurements –***

By utilizing Leica Geosystems proven slip-ring technology on both the vertical and horizontal axis the sensor has no rotational limits. It can rotate infinitely in all directions. By utilizing the quick release handle the sensor can measure 360° around the horizontal, and measure a full 290° dome over the vertical. When combined with an unmatched 160m range, this is truly the largest volume high accuracy sensor ever developed.

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**Leica Geosystems**

Metrology Products  
Moenchmattweg 5  
CH-5035 Unterentfelden  
Switzerland  
Phone +41 62 737 67 67  
Fax +41 62 737 68 68

**[www.leica-geosystems.com/metrology](http://www.leica-geosystems.com/metrology)**

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