EUCLID™: A High Accuracy, Position Compensated Laser Alignment System

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1. INTRODUCTION

The paper will discuss the development of a multi-target, precision laser alignment system. This commercial metrology system, *EUCLID*, was developed for precision and long range applications requiring extremely precise alignment of structures, tools, and assemblies in an industrial environment. The unique aspect of this system is its ability to reject measurement errors caused by movement of the laser beam. *EUCLID* does not use the laser beam as a datum, but instead uses two points defined by the user to be the established line of sight. The system uses transparent targets at alignment locations, and a reference target at the end of the line of sight. Optical target accuracy is 80 microinches (1σ) for a measurement range of +/- 0.05 inches; and 320 microinches for a measurement range of +/- 0.2 inches.

2. BRIEF REVIEW LASER ALIGNMENT TECHNOLOGY

In the mid-1960s the first laser alignment systems were developed. These early systems used a helium neon laser as the source. Usually, the 1 mm diameter of the laser was beam expanded to 8 to 12 mm to allow the beam to allow for good collimation over a reasonable range. The position sensitive target consisted of a quadcell; four photodetectors grouped together in a 2 x 2 arrangement. Laser beam position on the surface of the target was computed with analog signal processing. The first systems calculated the difference in the outputs of two photocells diagonally opposite to each other. The measurement signal produced was proportional to incident laser power. Variations in power due to atmospheric attenuation, power supply or temperature required manual adjustment of signal gain. The next development in the mid-1970s was to employ an integrated circuit analog divider. The measurement signal was now computed by dividing the difference of the two photocell outputs by their sum. The result was a signal that did not depend on incident laser power only laser beam position.

However, there remained many disadvantages. Significant ones were nonlinear measurement and a limited measurement range that was also sensitive to beam diameter. Once the laser beam was on one element of the quadcell, further beam movement was not detectable. A quadcell target would only have a practical range of operation of +/- 1/4 of a laser beam diameter. Reasonable linearity was achieved for +/- 1/8 beam diameter. The advent of lateral photodiodes in the late 1970s allowed for larger measurement ranges but targets still exhibited large linearity errors at measuring ranges occupying more than 50% of a lateral photodiode's active diameter.

Microprocessors appeared in the early 1980s and allowed greater flexibility and processing of signals.

3. SINGLE TARGET LASER ALIGNMENT

The main disadvantage of early laser alignment systems is that they only employed a single target. A target placed at a reference station establishes one end of the line of sight; the laser is the other end of the line of sight. The laser source is carefully aimed at the center of the target. Then the operator moves the target from its reference position and then proceeds to use it at intermediate locations.

There are two significant problems with single target laser alignment:

- The operator is unaware of any movement of the laser beam; and
- Alignment errors are introduced unless laser position at Reference is frequently checked

The only way to check for beam movement is to stop alignment operations, remove the target from its working location, and move it to the reference station position. The position of the laser beam on the target at the reference station is then checked, and the laser beam re-aimed, if necessary. This method is only useful for slow variations in laser beam position at the reference station caused by thermal disturbances in the structure being aligned, or in geologic influences at the laser source location. High frequency disturbances such as vibration resist effective countermeasures. Averaging helps but results in long response times.

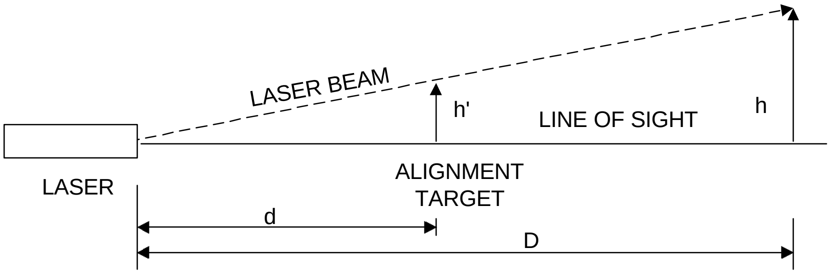
4. MULTI-TARGET LASER ALIGNMENT

The addition of a target situated at the end of the line of sight monitors beam position. The target used by the operator to allow passage of light to the Reference target is termed the Alignment or transparent target. If the two dimensional coordinates of the laser beam on the Reference and Alignment target are measured in real-time, the position of the Alignment target with respect to a line between the laser and the Reference target can be determined. Thus the laser beam need not be precisely aimed onto the center of the Reference target. Instead, the coordinates of the laser beam at both targets are used to compensate for any laser beam movement. When the position of the laser beam is sampled rapidly, the system compensates for thermal point errors, initial alignment errors, and vibration errors.

4.1 Pointing Compensation

In Figure 1 the line between the center of the Reference target and the center of the laser beam source defines the line of sight. The laser beam is shown directed upward, representing a laser pointing error. The transparent Alignment Target is shown centered with respect to the line of sight. The pointing error as measured at the Reference (R) target is h. Because of similar triangles the pointing error is h' or $(d/D)*h$ at the Alignment target. Subtracting this error from the measured beam position at the Alignment target results in a compensated (C) alignment measurement, or true position of the target in both the x and y axes:

$$C_{x,y} = h'_{x,y} - \frac{d}{D} h_{x,y}$$



True Position = h' - (d/D)h

Figure 1. Pointing Compensation

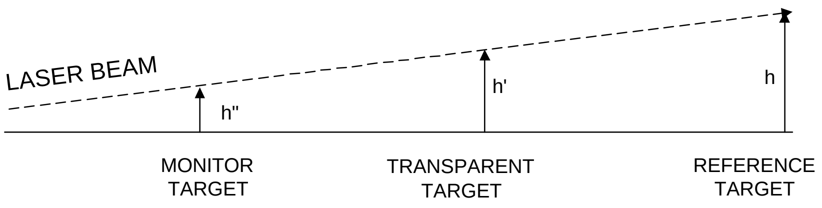
The reference datum is the line of sight. It is defined by two points: one point being the center of the laser case and the other being the center of the Reference Target. The constants d and D are measured in the field or have been previously entered into the computer. Absolute target distances are not required, only the ratiometric distance, d/D. In some applications absolute distances are known and entered into the computer or pendant prior to use. In other applications ratiometric distances are more convenient to use. In the field an operator can determine the ratiometric distance by intentionally pointing the laser beam by a small amount and determining the percentage change in laser beam position at both targets.

The targets sample laser beam position at 1000 Hz so that it is effective for use in high vibration environments. It is useful at long laser to target distances, as angular errors at the laser create large position errors at the targets. Another advantage of pointing compensation is that the operator does not have to precisely aim the laser to dead center on the target. This allows operators to quickly set up the system.

4.2 Pointing and Deviation Compensation

A more general method is used where deviation and pointing errors of the laser beam can be compensated. In this method the two points which establish the line of sight are the centers of two optical targets. An additional transparent target serves as a laser beam position monitor. For this more general compensation method the actual position of the laser beam is immaterial. The laser source can be remotely located and the two targets defining the line of sight be conveniently located. In Figure 2 a new variable h″ is required to measure the position of the laser beam as it passes through the first line of sight target. Again, ratiometric distances can be used instead of absolute distances for d and D for general compensation of pointing and deviation:

$$C_{x,y} = (h' - h'')_{x,y} - \frac{d}{D}(h - h'')_{x,y}$$



True Position of Transparent Target = (h' - h") - d/D(h - h")

Figure 2. Pointing and Deviation Compensation

5.0 SYSTEM ERROR SOURCES

The compensation method requires that the transparent target impose no steering or deviation of the laser beam as it passes through it. The system’s accuracy depends on the laser beam traveling in a straight line from the laser, through several targets and finally to the Reference Target. The transparent target has 3 mm thick windows on both ends, each possessing a small amount of wedge angle. There are two types of errors which can be injected into the compensation equations; that due to steering of the laser beam by the transparent target, and that due to deviation caused by the target being slightly tipped.

5.1 Target Steering

Rotation adjustment of the wedge prisms on the transparent target allows for the refractive error of the transparent target to be adjusted to less than one arcsecond. Figure 3 shows a two target system with the laser beam initially centered on the Alignment target.

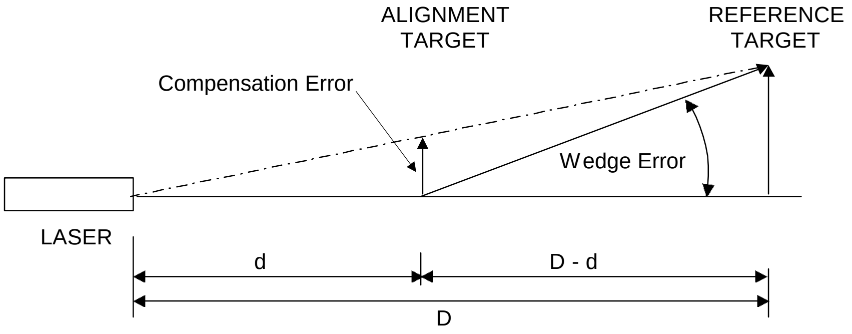


Figure 3. Compensation Error Caused by Laser Beam Steering at Alignment Target

The Alignment target is shown with a refractive error of δ and it steers the incident laser beam away from the line of sight. The laser beam strikes the surface of the Reference target at a distance of $(D-d)\delta$ from its center. The compensation algorithm then produces an error, ε, of magnitude:

$$\varepsilon = \frac{d}{D}\delta(D-d)$$

due to the wedge error δ of the transparent target. Inspection shows this error is zero when the alignment target is situated at a distance of 0 or D from the laser source. If the alignment target was situated next to the Reference target (d=D) it would impart no significant steering error at the Reference Target. If it were located next to the laser (d=0), the wedge error as seen at the Alignment target is also zero. Taking the derivative of the error term with respect to D and setting to zero finds that the error is greatest when the Alignment target is located halfway between the laser and Reference target; and falls off quadratically from this location.

Table 1 below shows how transparent target wedge error affects system alignment accuracy as a function of laser to Reference Target distance, D. The table assumes the alignment target is situated at D/2; or half the laser to Reference Target distance.

Table 1. Compensation Error Due to Residual Target Wedge Angle

[Inches (Microns)]

	Distance	Distance	Distance
Wedge δ	50 feet (15.25 m)	100 feet (30.5 m)	300 feet (91.5 m)
1 arcsec	0.00075 in. (19)	0.0015 in (38)	0.0045 in. (114)
0.5 arcsec	0.00037 in (11)	0.00075 in. (19)	0.0022 in. (57)

5.2 Target Deviation

The targets are designed to fit into precision 2.25 inch diameter bores. This NAS (National Aerospace Standard) mechanical interface is used for locating and mounting of optical tooling instruments. This universal mounting system consists of truncated 3.5 inch diameter steel spheres and mounting pedestal. These spheres are 2 inches thick and have a 2.25 inch diameter bore machined precisely though the center of the sphere. The optical target is inserted into the bore of the sphere and then the sphere is mounted onto a three point pedestal and clamped.

The location of the lateral photodiode sensor in the optical targets is such that the sensor appears to be located at the center of the sphere when the target's seating flange is located against the truncated sphere face. The purpose of this is that if the target is rotated in pitch or yaw that only a small cosine error is produced in the measurement. If the location of the sensor was not at the center of the sphere, the errors produced would be proportional to the product of the sine of the tipping angle and the distance from the center of the sphere. The targets can only be tipped by at most 3 degrees and the maximum error produced is when the laser beam is at the limits of its measurement range of 0.2 inches. This error amounts to only 0.0003 inches or 8 microns.

A somewhat larger error is made due to tipping of the target due to the deviation of the laser beam as it passes through the windows. In this case the deviation error cancels when the target is located halfway between the Referent Target and the laser, and is greatest at the Reference Target and laser. Also, deviation errors do not grow with distance as do pointing errors. Table 2 below indicates the magnitude of error due to target tipping in yaw or pitch. This error is greatest when the target is located at the laser or at the Reference target, and drops off linearly to zero midway between the laser and the Reference Target.

Table 2. Compensation Error Due to Target Tipping

[Inches (Microns)]

Tipping Angle	Error
1 degree	0.00066 in. (17)
3 degrees	0.00206 in. (51)

6.0 EUCLID DESCRIPTION

In the late 1980s QUEST established a design for a multi-target laser alignment system. The system would eliminate the requirement for precise initial alignment and frequent rechecking of the position of the laser on the Reference target. The fundamental difference between single target alignment was that the laser beam was not going to be used as the reference datum. Instead, the line of sight was going to be established by defined points. The targets would be transparent to allow measurement of the position of the laser beam on the Reference target. Multiple targets could be placed in the laser beam to monitor many positions simultaneously. The mechanical center of the Reference target would define one end of the line of sight and the center of laser source the other. The system electronics were designed around a high-speed serial bus architecture. Each target measures laser beam position in synchronism to a timing signal and transmits its data to a host computer when commanded. The minimum system consists of:

- Power supply with bus/computer interface
- Transparent Alignment Target
- Reference Target
- Interconnect Cables
- Laser source
- Graphical Alignment Pendant (or PC)

Figure 4 shows the system components of *EUCLID*. They consist of: (clockwise, starting at upper left corner) system power supply, graphical pendant, system cables, Reference Target, solid state 635 nm modulated laser, and transparent Alignment Target. Not shown is the instrument case which protects all the components.

Figure 4. ***EUCLID*** **Components**

6.1 Optical Targets

The targets and laser are manufactured to NAS tooling dimensions (2.2497 inch diameter barrels.) The electronics of each target consist of a digital signal processor (DSP); non-volatile, electrically erasable programmable memory (EEPROM), dual 16 bit analog-to-digital converters, filters, and serial communication drivers. The targets each use a large active area lateral photodiode detector to sense laser beam position; the transparent Alignment target uses a specially coated pellicle beamsplitter to redirect approximately 20% of the incident laser beam intensity onto the detector. Up to 6 transparent Alignment targets can be placed in the beam without degrading system accuracy.

After the targets are assembled and tested they are placed on a precision Cartesian robot. This robot has a NIST certification of linear accuracy of +/-20 microinches per inch of travel. The target is moved relative to the laser beam in 0.01 inch increments over a mapping area of 0.4 inches by 0.4 inches; the robot's position accuracy over this range is +/- 8 microinches. The result is a map capturing all non-linearities contained in the detector and electronics. The laser beam is Gaussian to 300 feet and there is virtually no error due variable or asymmetric intensity profile of the beam. Raw data from the detector is corrected in real-time using the DSP. The technique used is a 5th order polynomial least squares curve fit. The resulting dimensional data is sent to the operator's pendant or personal computer over a high speed RS-485 serial bus. This technique linearizes raw data from the lateral photodiode into engineering units.

After mapping is complete, the average, minimum and maximum errors and the standard deviation in both axes are determined and stored as a calibration data for the target. The EEPROM holds the coefficients for the polynomial equation used to convert raw data into calibrated data. One benefit of this design is that a more precise calibration can be applied to the target by moving it in smaller steps over a smaller region. The table below indicates the one sigma accuracies for a target for two different calibrations. To produce a higher accuracy target involves loading a different file into the target's nonvolatile memory.

6.2 Alignment Laser

The laser source uses a modulated laser diode operating at a wavelength of 635 nanometers. The highly divergent light from the laser diode is collected with a pair of aspheric lenses mounted vertex to vertex. The light is focused by the second lens onto the end of a single mode, polarization preserving fiber. The distal end of the fiber is placed at the focal point of a well corrected, medium fast, achromatic lens. This type of laser source produces a collimated beam that has an almost perfect Gaussian intensity profile. This is crucial to achieving high target accuracy because the lateral photodiodes detector reports the position of the centroid of the incident laser beam. If the intensity profile of the laser beam is not Gaussian, the target does not accurately sense the true position of the center of the beam. The fiber-coupled diode/achromatic lens arrangement results in a collimated beam with a measured M-squared factor of 1.02, exhibiting a diffractive divergence only 2% above that of a single mode He-Ne laser beam. The degree of Gaussian fit to a cross section profile is 99% or greater. A beam of this quality produces higher target position accuracy than laser diode coupling and collimation methods employing cylindrical lenses and anamorphic prisms. Practically, it allows interchangeability between lasers and targets.

6.3 System Operation

Either a pendant or PC controls the flow of data from the targets as well as functioning as a display device. The basic target position measurement consists of the difference between two position values obtained with the laser beam on and a value with the laser beam off. This synchronous detection process is done at the laser modulation frequency of 10 kHz and eliminates measurement errors due to ambient light. When a target measurement is required, the system host broadcasts a message to all connected targets. Each target then takes basic position data for a predefined number of times and computes the mean. The system host then requests transmission of measurement data in sequence from each connected target. The pendant or PC then calculates the true Alignment target position using either the pointing or general compensation method previously described.

When a PC is used as the system controller, a data configuration file representing measurement variables and geometry is downloaded into the targets prior to use. If the pendant is used, the current configuration stored in memory is used. The pendant has a button which the operator can use to select predefined target positions.

The optical targets can be corrected in the field for simple offsets by rotating a target 180 degrees and pressing a button after each rotation. Half the difference in both the X and Y values at each position is used as an offset that is stored in nonvolatile target memory.

7.0 APPLICATION AREAS

EUCLID is useful in application areas where high accuracy, fast system setup and remote monitoring or logging of data is required. It rejects effects of both slow and high speed movement of the laser beam by canceling common mode position signals at the targets. Its beam emerges from a fiber coupled diode laser and has a cross section intensity profile that is virtually indistinguishable from a helium-neon laser.

Some applications areas include:

- Aerospace structures for tooling, assembly and manufacture
- Alignment of particle accelerator components
- Monitoring of structure or tunnel wall movement
- Machine tool path correction due to load dependent forces

8.0 CONCLUSIONS

A laser alignment system which produces accurate measurements independent of the position of the beam on its targets has been described. A similar triangles compensation method is used to describe the true position of targets with respect to a line of sight. The line of sight is defined by two points; either the center of the laser and the Reference Target, or the centers of a transparent monitor target and the Reference Target. The optical targets comprising the system use a lateral effect photodiode and 16 bit analog signal processing to achieve high resolution; linearization of detector signals is done via a DSP inside each target using coefficients stored in nonvolatile memory inside each target.

This commercial system is used to align structures and can also monitor movement with its data logging function. Its main features are:

- The fiber-coupled laser diode source projects a Gaussian beam to 300 feet and can be considered a replacement for a He-Ne laser
- Lasers and targets are interchangeable
- 1-sigma target accuracy of <0.00032 inches (8 microns) for a +/- 0.2 inch (+/- 5 mm) measurement range and <0.00008 inches (2 microns) for a +/- 0.05 inch (+/- 1.25 mm) measurement range.