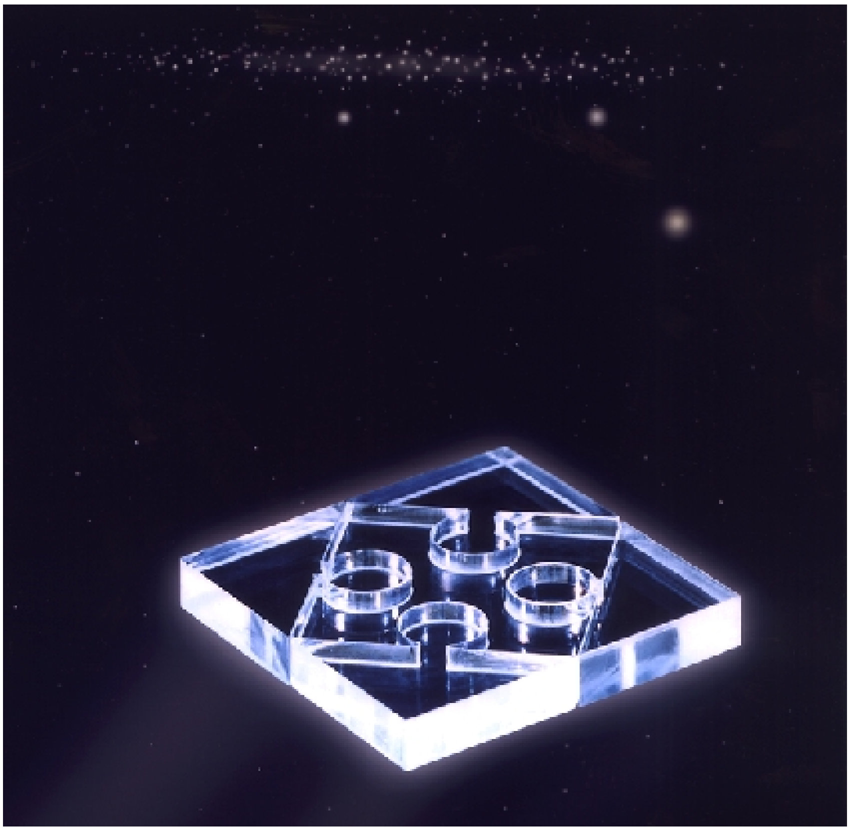
Axyz

Dictionary of 3D Metrology



Leica AG PMU, Unterentfelden

Authorship

Created and compiled by: Dr. Stephen Kyle, Leica
Academic review by:
Aerospace review by:
Automotive review by:

Proprietary information

The ***Axyz*** program has been developed by Leica Geosystems, Switzerland and Atlanta USA.

This manual was produced using Microsoft Word. and *Doc-To-Help*® (WexTech Systems, Inc.)

Document reference data

Title:	***Axyz*** Dictionary of 3D Metrology
Order number:	n/a
Software version:	1.4
Document release date:	December 1999

Contents

Introduction to the dictionary of metrology

Objective and scope of the dictionary

The dictionary provides access to some 500 definitions and terms which are useful in describing, explaining and discussing the field of large scale metrology. The author welcomes suggestions for corrections, modifications and additions. Please e-mail Stephen_Kyle@compuserve.com.

How the terms have been compiled

An alphabetical division of definitions is provided by heading level one. Heading level two provides most of the *primary definitions.* These terms and definitions represent preferred usage or are the main source of a number of derived terms and definitions.

Terms which are mentioned within the text, and which have an explicit primary definition, are shown in *italics*. For example, the definition of *corner cube* makes reference to *retro-reflector, laser tracker* and *Total Station.* These last 3 items all have an explicit definition.

For convenience some related terms only appear within the text of other definitions and are therefore defined by their context. These are shown in **bold type** and appear in the index. For example, the definition of *corner cube* makes reference to **air-path corner cube, hollow corner cube** and **prism retro-reflector**. These last 3 are only defined by the description of *corner cube* but can be found in the index. Alternative terms for ***Axyz*** primary definitions may be in current usage. In this case, known alternatives are either listed or used within the explanation of the corresponding primary term. These are also shown in **bold type** and appear in the index.

Abbreviations and acronyms are inserted in the alphabetical listing along with normal terms. These are also separately summarized.

If the term you are searching for does not appear in the alphabetical listing then try the index.

To prevent some entries from becoming too large or complex, related terms are sometimes given a full entry as, for example, *tracker*, *tracker alignment*, *tracker alignment parameters* and *tracker alignment techniques*. These are cross linked to one another.

Summary of acronyms and abbreviations

ADM

Short for *Absolute Distance Meter*.

AM

Short for *Amplitude Modulation*, Amplitude Modulated.

AP

Short for **Application Processor.**

ATMS

Short for Automated Theodolite Measuring System.
This was an automated *triangulation* system based on remotely driven motorized theodolites and electronic imaging of the telescope's field of view. It was manufactured by *Wild* Heerbrugg. (No longer in production.)

CAD

Short for computer-aided design.

CCD

Short for *Charge Coupled Device.*

CDM

Short for **Core Data Module**, one of the ***Axyz*** software modules.

CMM

Short for *Coordinate Measuring Machine.*

CS

Short for *Coordinate System*

DD

Short for Decimal Degrees.

DM

Short for **Data Manager**, one of the ***Axyz*** software modules.

ECDS

Short for Electronic Coordinate Determination System.

This was one of Leica's earlier 3D coordinate systems based on theodolites. It was manufactured by *Kern* Swiss.

EDM

Short for *Electromagnetic Distance Measurement*, Electronic Distance Meter

ERS

Short for *Enhanced Reference System.*

FM

Short for *Frequency Modulation*, Frequency Modulated.

GSI

Short for Geodetic Services, Inc.
Manufacturers of software and hardware for industrial *photogrammetry*.
The company is based in Melbourne, Florida, USA.

Hz

Short for Hertz.
International symbol for frequency, meaning "cycles per second".
Named after the German physicist, Heinrich Rudolf Hertz.

ID

Short for Identifier.
A string of alpha-numeric characters which identify or name a particular item of data.

IFM

Short for *Interferometer*.

INCA

Short for INtelligent CAmera.

This digital camera is manufactured by Geodetic Services, Inc. and has its own computer for on-board image processing.

See also *camera*.

IR

Short for infrared *light*.

LAN

Short for *Local Area Network.*

LED

Short for Light Emitting *Diode*

LTM

Short for **Laser Tracker Module**, one of the ***Axyz*** software modules.

ManCAT

Short for Manual Computer Aided Theodolite system.

This was one of Leica's earlier 3D coordinate systems based on theodolites. It was manufactured by *Wild* Heerbrugg.

MTM

Short for **Multiple Theodolite Module**, one of the ***Axyz*** software modules.

PSD

Short for *Position Sensing Device.*

RMS

Short for *Root Mean Square.*

SMART

Short for System for Mobile Angle and Ranging to Target.

This was the first commercial version of Leica's laser *tracker*. It was manufactured by *Kern* Swiss.

SMR

Short for **Spherically Mounted Retro-reflector**.

SPACE

Short for System for Positioning and Automated Coordinate Evaluation.

This was an automated *triangulation* system based on remotely driven motorized theodolites and electronic imaging of the telescope's field of view. It was manufactured by *Kern* Swiss. (No longer in production.)

STM

Short for **Single Theodolite Module**, one of the ***Axyz*** software modules.

TP

Short for **Tracker Processor.**

TBR

Short for **Tooling Ball Reflector**.

UV

Short for ultraviolet *light*.

VSTARS

Short for Video Stereo Triangulation And Resection System.

Name of a commercial video triangulation system built by Geodetic Services Inc., Florida, USA (GSI) and sold by GSI and Leica.

1,2,3

2-face measurement

A 2-face measurement is a pair of measurements made by pointing a theodolite telescope or tracker mirror in its two *face* positions to the same fixed target.

Instruments which are in good adjustment and have well corrected measurements will give the same value of the pointing or polar measurement in both positions, except for *random error*.

2-face measurements are used to:

- Check the correct operation of an instrument
- Eliminate a number of *systematic errors*
- Enable error models to be calculated for purposes of calibration or alignment

Alternatives:
Two face measurement

3D

3 Dimensional or 3 Dimensions

Relating to spatial information in 3 dimensions.

3D transformation

Diagram: 3D transformation
This is a technique for calculating a new coordinate system based on a best fit between points with coordinates known in an existing system and in the new system. The best-fit calculation uses the technique of least squares.

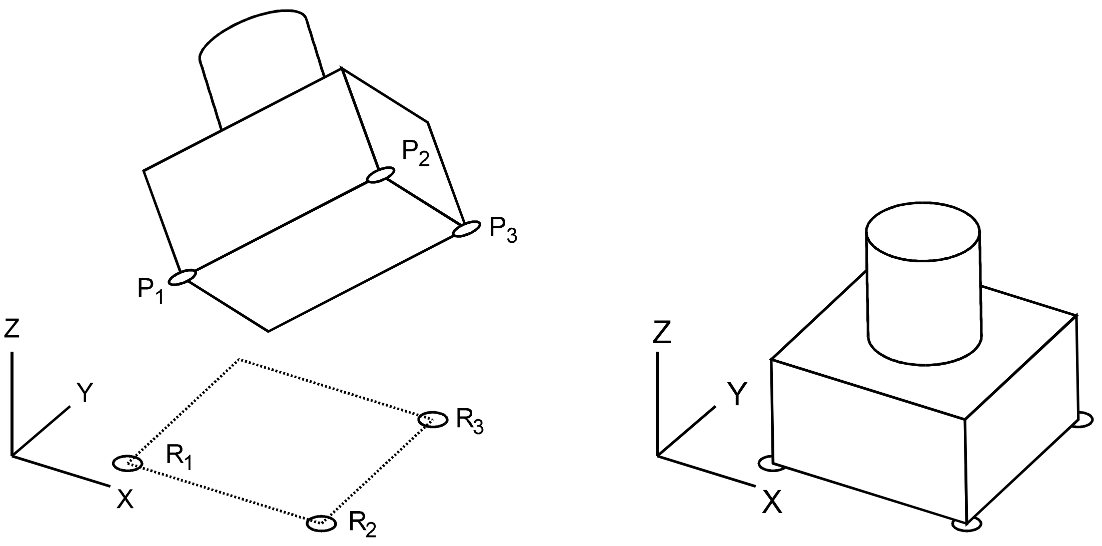
The diagram shows how some measured points P1, P2, P3 on an object are transformed by best fit onto reference values R1, R2, R3. The calculation generates 7 **transformation parameters**. The 6 parameters are 3 shifts along the coordinate axes and 3 *rotation parameters*. The 7th. parameter is a potential scale change.

The transformation parameters can then be used to transform any other measured 3D data into the reference system, a process known as **coordinate transformation**.

Alternatives:
Least squares transformation
Best-fit transformation
Similarity transform

See also *axis alignment*.

Diagram: 3D transformation



Basic principle of 3D transfromation TRF3D.WMF

3-2-1 transformation

A 3-2-1 transformation is a *3D transformation* carried out with the minimum number of reference coordinate elements. Normally a 3D transformation requires full coordinate information at 3 reference points, not all on a straight line. However it is possible to calculate a transformation when some reference points have only partially known coordinates. For example in a levelled reference system you might have the following:

- One point has all 3 elements known (3)
- One point is only known on the horizontal XY plane, i.e. it can be anywhere on a vertical line through the defined horizontal position (2)

- One point only has a known height, i.e. it lies somewhere on a particular horizontal plane (1)

When minimum data is used to calculate the transformation, more than one solution is theoretically possible. This could, for example, cause an object to be transformed into the upside down position. As a result, the unknown reference values must be approximately known in order to force the solution into the correct result.

As an alternative to 3-2-1 transformation, *axis alignment* may be used. Axis alignment may also be used to generate initial transformation parameters for a 3-2-1 transformation.

7-parameter transformation

A 7-parameter transformation normally refers to the 7 parameters which effect a spatial movement and scale change of an object or a conversion (transformation) between *coordinate systems*.

3 parameters are the coordinates which represent the difference between coordinate system origins or an equivalent point on a shifted object.

3 parameters relate to the relative tilts of the coordinate axes or shifted object.

One parameter is a scale factor which can accommodate a difference in scale between the coordinate systems or shifted objects.

Axyz uses the methods of *3D transformation* and *axis alignment* to calculation the appropriate parameters in the case of coordinate systems.

See also *degrees of freedom*.

A

a posteriori

A Latin term translating literally as "from the latter" (from effect to cause).

It is typically used to describe a statistical value derived <u>after</u> some data processing. For example, after fitting a set of points to a circle an a posteriori *variance factor* can be calculated.

a priori

A Latin term translating literally as "from the previous" (from cause to effect).

It is typically used to describe a statistical value estimated before some data processing. For example, before fitting a set of points to a circle each point will have a previously known and estimated a priori **standard deviation**.

Aberration

Diagram: Chromatic aberration
Diagram: Spherical aberration
Diagram: Coma
Diagram: Astigmatism geometry
Diagram: Astigmatism focus
Lenses are intended to produce good quality images so that instruments used in large scale metrology such as *telescopes* and *cameras* produce optimal accuracy. Unfortunately all lenses suffer from defects known as aberrations which affect image quality and the ability to make accurate measurements. Proper lens and instrument design can considerably eliminate them or reduce their effects.

Lens distortion is the most obvious aberration to the casual observer. It results in sharp images which are distorted due to varying scale. See the fuller entry on this item.

The following aberrations affect image quality by ensuring that a sharp image cannot be obtained.

- **Chromatic aberration**
  Blue light is refracted more than red so that the blue image components are closer to the lens than the red ones
- **Spherical aberration**
  Monochromatic light is refracted more at the edge of the lens than the middle, so that edge rays image closer to the lens than central rays.
- **Coma**
  Oblique rays from an off-axis point converge in an unsymmetrical way. On one side they are refracted too much, on the other too little. A comet shaped image spot results, hence the name.
- **Astigmatism**
  To an off-axis point a circular lens looks elliptical and the axes of the ellipse represent two perpendicular planes in which the focal length is different. The diagram shows a cross-shaped image which can only be sharply focused in either a radial or tangential direction.
- **Curvature of field**
  The image plane should ideally be flat for that is the most convenient way to record it on film or electronic chip. However it is curved, ensuring that a sharp image cannot be obtained across a flat recording surface.

Taken together all these distortions and aberrations ensure that measured image locations are not at their "ideal" position. At any particular location in the image, the net error is considered to have two components. **Radial distortion** is the offset in a direction away from the centre of the image. **Tangential distortion** is the offset perpendicular to this.

Diagram: Chromatic aberration

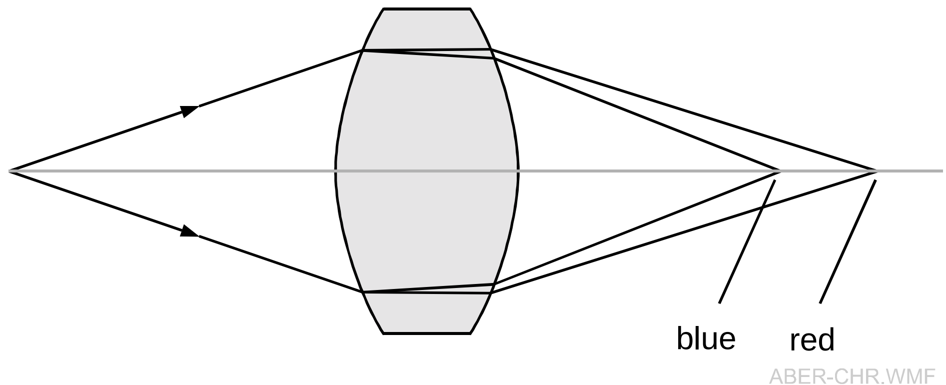


Diagram: Spherical aberration

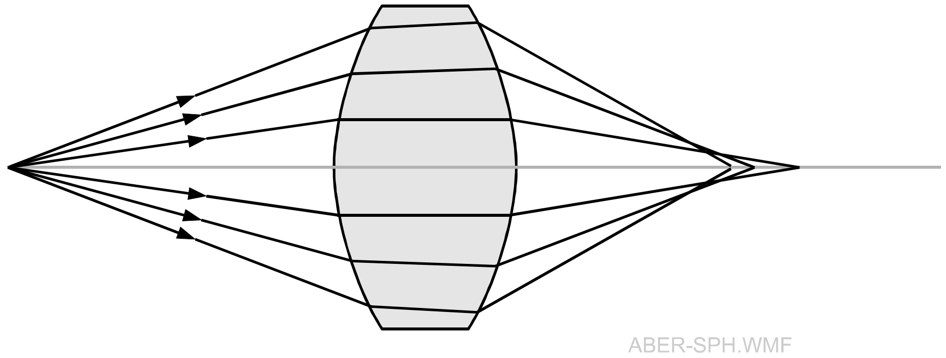


Diagram: Coma

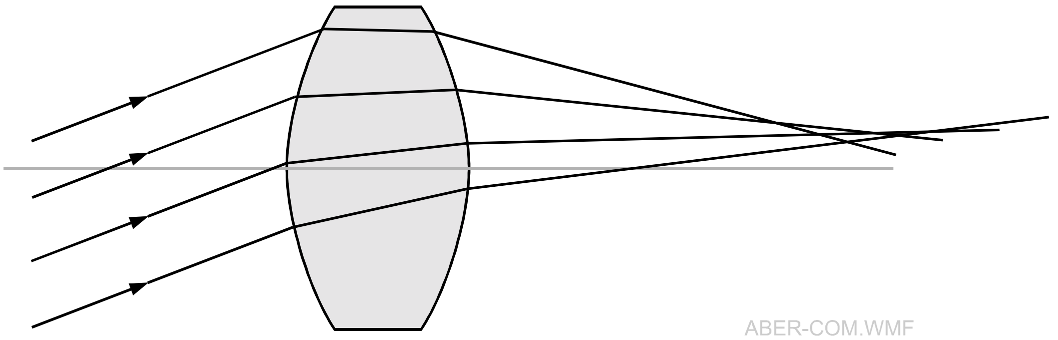


Diagram: Astigmatism geometry

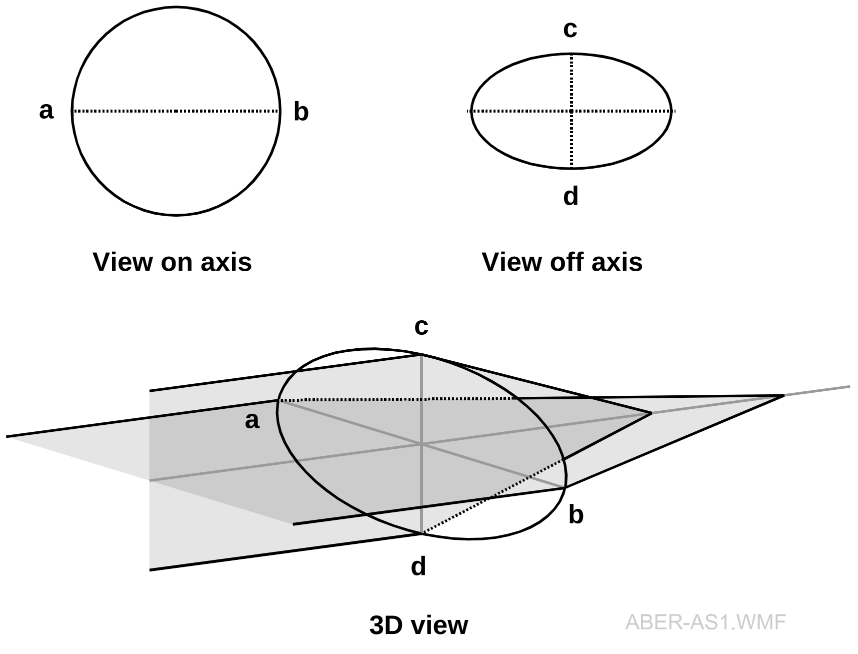
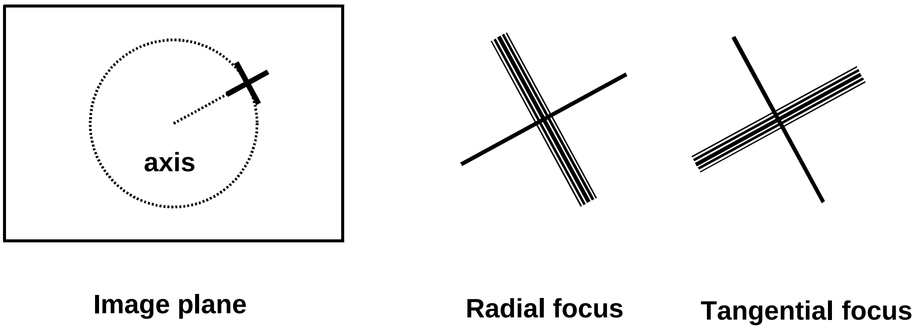


Diagram: Astigmatism focus



ABER-AS2.WMF

Absolute Distance Meter (ADM)

The ADM is another form of *Electronic Distance Meter (EDM)*. Unlike standard EDM methods based on amplitude modulation, it uses a technique based on modulated **polarization**.

Laser light is polarized and the plane of polarization can be modulated in a sinusoidal wave pattern. The frequency of modulation is adjusted so that an exact number of wavelengths fits the distance being measured. Knowledge of the physical conditions and frequency ensures that the wavelength is known, but the number of whole wavelengths (n) is unknown. The distance cannot yet be calculated. A second measurement is therefore made at a slightly higher frequency such that one more full wavelength (n+1) fits into the measured path length.

In calculating the distance (d) the two measurements generate two equations. Since there are only two unknowns, d and n, it is therefore possible to compute both d and n.

The technique is very precise due to a combination of factors:

- The use of modulated polarized light
- Frequency adjustment to an exact number of whole wavelengths
- High modulation frequency in range 750 MHz to 920 MHz

Acceptance angle

In relation to *retro-reflectors* this is defined by the maximum angular offset from the axis of the reflector of an incoming ray which is still returned by the reflector.

Accuracy

An estimate of how close a measured quantity is to its true value.

ADM

Short for *Absolute Distance Meter*.

Algorithm

A particular computational procedure for calculating one or more values. Different algorithms may be available to calculate the same values.

For example, a flash photograph of a circular target made of adhesive retro-reflective material appears in an electronic image as an elliptical spot on a black background. Each individual picture element (**pixel**) has a grey level value where zero means black and 256 means white. Most of the target pixels will have a grey level value close to white but drop towards black at the edge.
Different algorithms could be used to find the centre of the target:

Algorithm 1:
1. Look for the first pixel with a value of 256.
2. Assume the centre of this pixel is the centre of the target.

This is an inaccurate algorithm and it may not give a unique value.

Algorithm 2:
1. At different locations examine the edge pixels (changeover between white and black)
2. At each location fit a curve through the edge pixel values and choose a standard point on the curve which represents the "edge"
3. Fit an ellipse to all the edge points
4. Calculate the centre of the ellipse.

This is a much better algorithm for finding the centre.

Alignment

1) Relating to *optical tooling*
The condition that components of a measured object lie on a straight line, parallel lines or lines which intersect at right angles. When you **align** components you physically adjust them into alignment.

2) Relating to *laser tracker*

The small amounts by which components in the laser tracker are not exactly in alignment. When you **align** a tracker you make measurements to calculate these amounts. These values are then used as the parameters of a software model which corrects the instrument readings. Components are not physically adjusted. See *tracker alignment*.

AM

Short for *Amplitude Modulation*, Amplitude Modulated.

Amplitude modulation (AM)

Electromagnetic signals (light beams or radio waves) used to make measurements or carry information are built up from sine waves of known frequency. The amplitude of the sine wave indicates the energy in the beam. A bright laser beam contains light of one frequency with a large amplitude.

The amplitude may itself be modulated in a sinusoidal way. For example, a laser beam could be passed through an adjustable polarizing filter so that its brightness varies continuously. The wavelength of the modulation is much larger than the wavelength of the underlying **carrier signal**.

The component of the beam which represents the amplitude modulation may be used to measure distance.

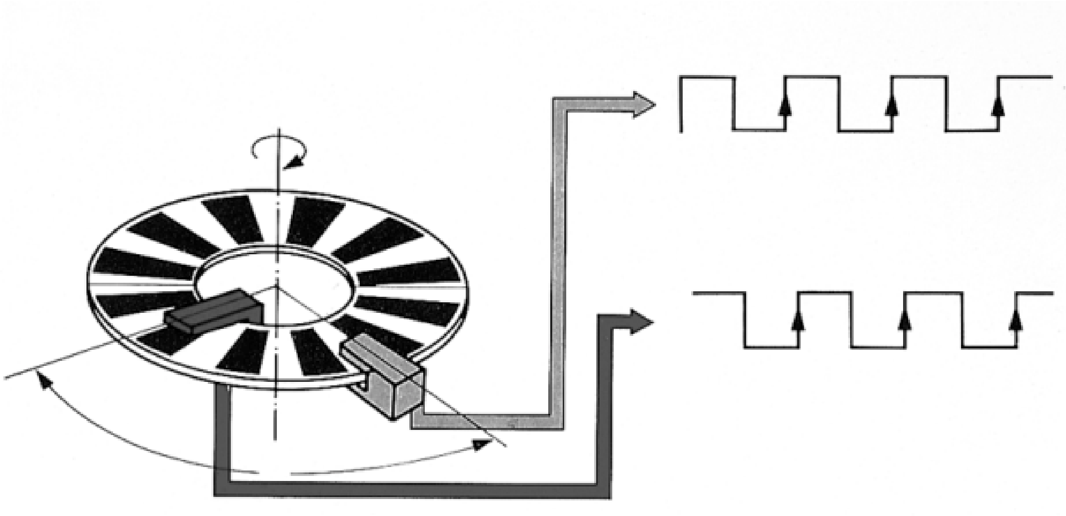
As an alternative to modulating the amplitude, the carrier signal may be *frequency modulated*.

Angle encoder

Diagram: Absolute angle encoder
Principle: Absolute angle encoder
A device which electronically measures an angle of rotation. Angle encoders are used in theodolites, Total Stations and laser trackers to measure horizontal and vertical angles.

See the sub-text for operation of the absolute encoders used in Leica theodolites.

Diagram: Absolute angle encoder



Principle: Absolute angle encoder

The encoder for measuring the horizontal and vertical angles is based on an engraved glass circle which rotates at constant speed.

Angle measurement employs a sensor fixed to the instrument which defines the zero direction. Two further diametrically opposed sensors rotate according to the telescope pointing. (Only one is shown.) By counting divisions between the fixed sensor and a moving sensor the angular movement can be measured.

The circle rotates at constant speed and measurement is dynamic, providing 512 measurements of the angle per revolution. The recorded value is the average of these. This technique eliminates small inequalities in the circle divisions.

AP

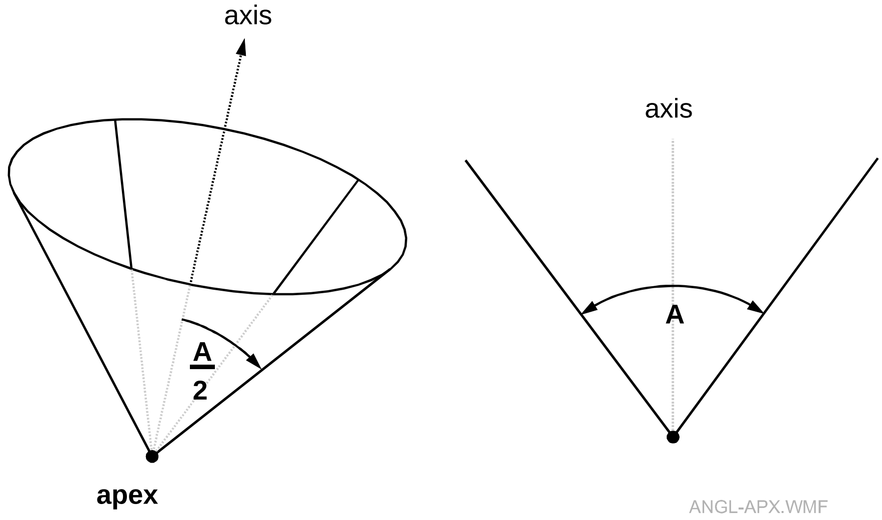
Short for **Application Processor.**

Apex angle

Diagram: Apex angle of cone
1) The angle formed at the intersection of two lines or directions.

2) The angle at the apex (tip) of a cone. This angle is specified as twice the angle between the axis of symmetry of the cone and a line on the surface through the apex (a generating line of the cone). The diagram indicates apex angle A.

Diagram: Apex angle of cone



ATMS

Short for Automated Theodolite Measuring System.

This was an automated *triangulation* system based on remotely driven motorized theodolites and electronic imaging of the telescope's field of view. It was manufactured by *Wild* Heerbrugg. (No longer in production.)

Average

A single representative value for a set of values calculated by adding the individual values and dividing by their total number. For N values v_1 .. v_N

$$\text{Average} = \frac{\sum_{1}^{N} v_i}{N}$$

Note
Do not confuse the alternative name "mean value" with *mean error*.

Alternatives:
average value
mean
mean value
arithmetic mean

Axis

1. A real or imaginary line about which an object, such as an aircraft, can rotate.

2. A line of symmetry.

3. One of two or three reference lines used in coordinate geometry to locate a point on a plane or in 3D space.

Axis alignment

Maths for Users, s. 5.7.3, p.1

Axis alignment creates a new object coordinate system by aligning new axes to directions and planes defined by the object points. The new axes may be freely oriented to object points or they may be placed in the object but additionally oriented to gravity. The technique defines a new right-handed system of axes.
The procedure generates 7 **transformation parameters**. 6 parameters are an origin change in 3 directions and 3 *rotation parameters* to re-direct the axes. The 7th. parameter allows for a scale change.

The transformation parameters can then be used to transform any data from the old coordinate system into the new, a process known as **coordinate transformation**.

See also *3D transformation*.

Axyz

Diagram: ***Axyz*** components
Axyz (pronounced AX-IZ to rhyme with quiz) is a system comprising a computer controlled set of optical instruments and related software which is used for large-scale 3D metrology. It can generate, on line, the 3D coordinates of selected object points and provides a wide range of analysis functions to process this object point data.

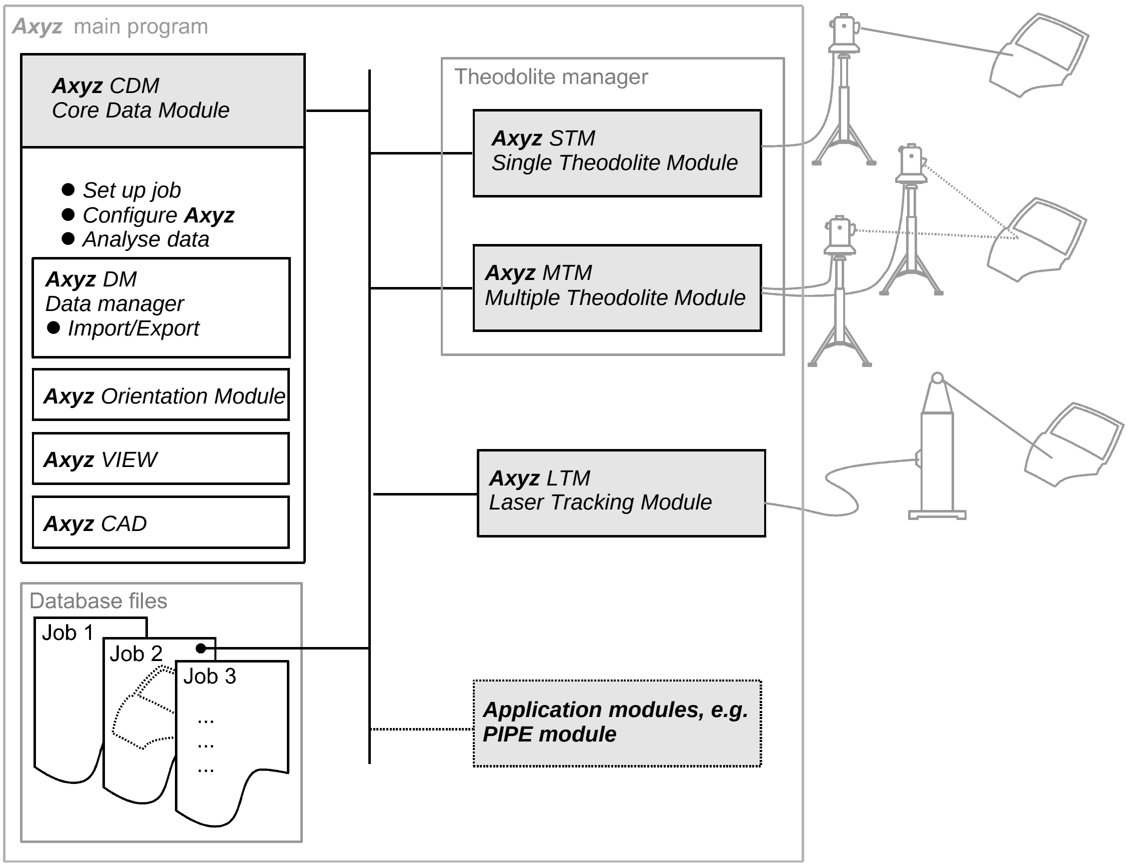
The optical instruments currently include precision electronic industrial theodolites, Total Stations and laser trackers. (Jan. 99).

These optical instruments utilize the techniques of *triangulation* and *polar measurement* to derive the 3D coordinates of selected points on manufactured objects and components.

The ***Axyz*** software is divided into a number of modules which can be summarized as follows:

- **Core Data Module (CDM)**
  Measurement job administration and 3D analysis functions
- **Data Manager (DM)**
  Provides a numerical view of job data in spreadsheet format
- **Orientation module**
  Calculates location and orientation of instruments
- **Graphics module** (***Axyz*** **View** or ***Axyz*** **CAD**)
  Provides a graphical view of the data
- **Theodolite manager**
  Configures the **MTM** and **STM** modules
- **Multiple Theodolite Module (MTM)**
  Supervises the operation of multiple theodolites and Total Stations
- **Single Theodolite Module (STM)**
  Supervises the operation of a single Total Station
- **Laser Tracker Module (LTM)**
  Supervises the operation of a laser tracker

Diagram: Axyz components



Leica *Structure of **Axyz** industrial measurement system* AXYZ.WMF

Azimuth angle

Diagram: Azimuth angle

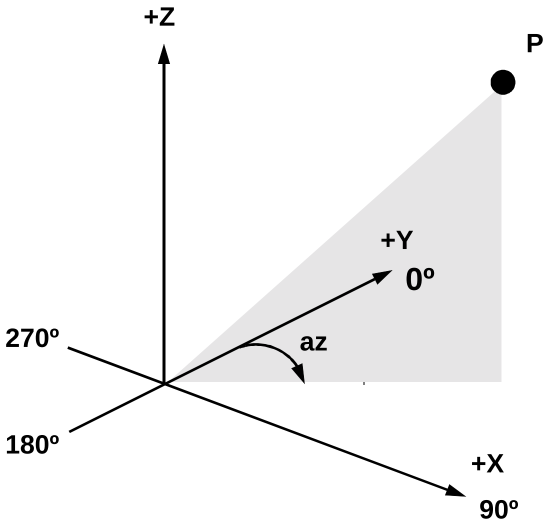
An angle measured in the horizontal plane using the **horizontal circle** of a theodolite, Total Station or laser tracker.

In a conventional right handed coordinate system (X,Y,Z) where X and Y are the axes in the horizontal plane and Z is the vertical axis, the angle is measured positively from the Y axis towards the X axis.

Sometimes it is loosely called the *horizontal angle* but this angle is correctly measured in the opposite direction, from the X axis towards the Y axis.

The term is also commonly used even if the instrument is only approximately levelled.

Diagram: Azimuth angle



Azimuth angle, az

ANGL-AZ.WMF

B

Balanced station network

A balanced station network has similarities with a *free net adjustment* and is designed to remove an inconsistency in the quality analysis which results when an arbitrary datum is specified for the *bundle adjustment*, used to optimize the network *orientation*. When the datum is arbitrary the coordinates of the origin are assigned zero error. Since errors are relative this does not affect the quality analysis of derived elements such as the distance between two points but it does affect the errors estimated for coordinates. The balanced network distributes these in a more even-handed way.

Ball Bar

Photo: Laser tracker Ball Bar

1) For the laser tracker

A calibration device for a laser tracker which moves a target retro-reflector in a precisely defined circle.

The device has an arm of fixed length which is rotated by a motor. At the extremity of the arm is a holder for a retro-reflector. The arm is intended to rotate in an approximately vertical plane.

By tracking the reflector the measured path can be compared with a circle. This can be used either to check the operation of the instrument or to provide input data for *tracker alignment.*

2) Fixed length bar for CMM

For checking a CMM, a fixed length **ballbar** has two spherical elements joined by a bar of fixed length. Under standard conditions the separation of the sphere centres has an accurately known value.

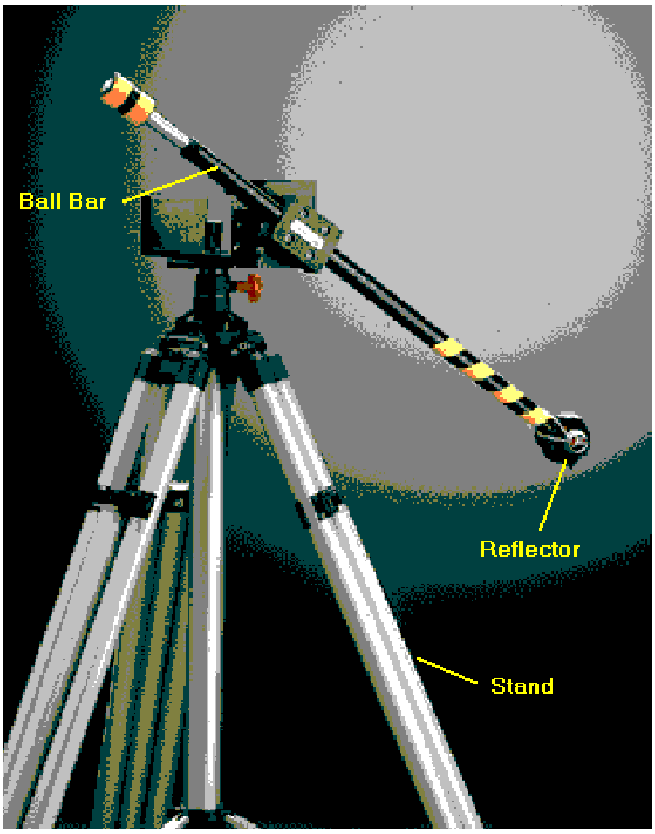
By measuring the sphere centres with a CMM, a measured separation can be calculated and compared with the reference value for checking purposes.

For ***Axyz*** users the device is equivalent to a *scale bar*.

3) Compliant length bar for CMM

A more sophisticated **ballbar** for checking CMMs has a slightly variable length. Like a fixed length bar, this bar has a spherical surface at each end. One end of the bar is magnetically located in a mounting fixed to the CMM base. The other end is magnetically located at the probing point. The CMM is programmed to trace nominal circles. Small imperfections in the circle are detected by changes in the length of the ballbar.

Photo: Laser tracker Ball Bar



Base coordinate system

The initial *coordinate system* created by a network *orientation*.

Often the base system's origin and axes are defined by the first instrument in the network and this is commonly the case if only one measuring station exists.

In some cases the system lies close to an instrument's origin and axes but is not identical with them. This is likely with a *balanced station network.*

The origin and axes of a base coordinate system can also be defined by object features. This occurs when the network orientation is calculated by *orientation to control*.

Base coordinates

Coordinates measured in the *base coordinate system*.

Birdbath

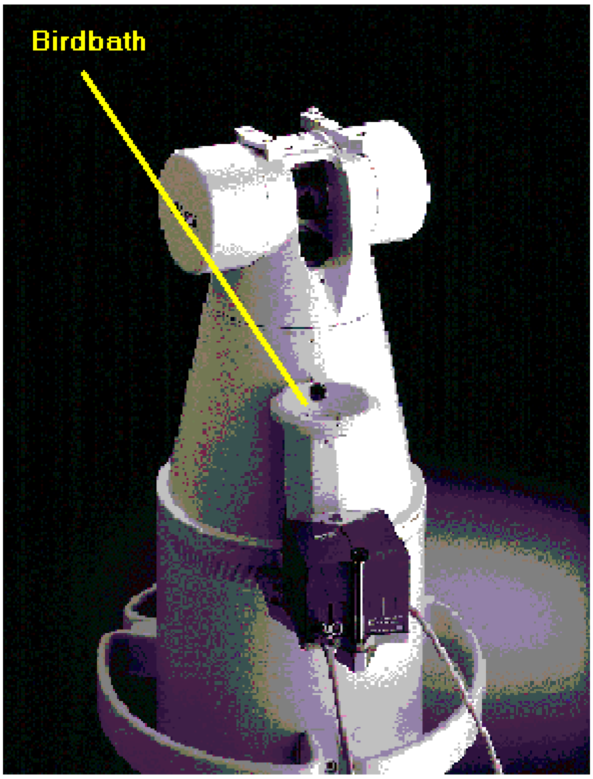
Photo: Birdbath

The *laser tracker* uses an interferometer for distance measurement but it can only measures a change of distance, not an absolute distance. In order for it to provide the absolute distance to a reflector it must start or re-start measurement from a location whose distance is already known.

The tracker is therefore equipped with a fixture, commonly called a Birdbath, which ensures that such a location is always available. The name is used because of its visual similarity to a Birdbath you might place in the garden. The corresponding distance is the *Birdbath distance*.

The conventional name for the Birdbath is **Home point**. Leica's *SMART* system, which was the first laser tracker in production, referred to this point as **Home point zero**. SMART allowed the designation of any currently measured and fixed point as a "home point", each of which had a number, hence the need to designate the Birdbath with the ID zero.

Photo: Birdbath



Birdbath distance

The Birdbath distance is the distance from the rotation centre of the tracker to the centre of the reflector when sitting in the *Birdbath*. It is one of the critical tracker parameters. Any error in this value directly affects distance measurement.

Since reflectors have housings of different sizes and may have different internal optical path lengths (glass prisms, cat's-eye elements), the Birdbath distance is different for every type of reflector.

Blunder

A totally incorrect measurement or mistake, e.g.
- sighting wrong target,
- electronic corruption of a data

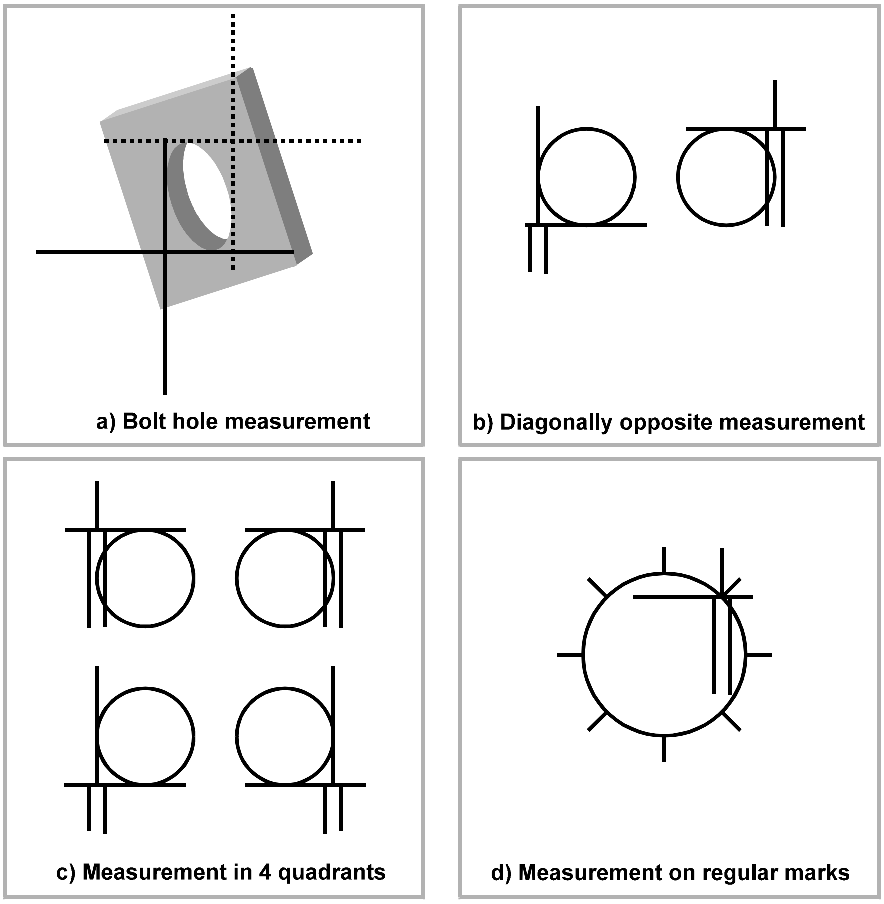
Blunder detection is a feature in a *bundle adjustment* which automatically finds blunders.

Alternatives:
mistake

Bolt hole

Diagram: Bolt hole measurement
A type of point measured with theodolites. The pointing to the centre of the bolt hole is determined by the use of edge measurements with the telescope cross-hairs:

Diagram: Bolt hole measurement

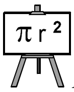


BOLT-HLE.WMF

Build

To construct or physically adjust components of a manufactured object such that critical points are placed in their design locations.

Bundle adjustment



Maths for Users, s.8.1 p1.

A bundle adjustment is the name given to a general *least squares* technique which is used to optimize a network *orientation.*

The adjustment takes the bundles of pointings to identified targets from theodolites, Total Stations, trackers or cameras and processes them to create an optimal set of station parameters and target coordinates which is a best fit to the angular and distance measurements made.

For variations on the technique, see also *free net adjustment* and *balanced station network.*

C

CAD

Short for computer-aided design.

Calculated point

A point derived by calculation, such as the intersection of two lines. A derived point such as the local origin of a calculated shape may also be stored as a calculated point.

See *point* for a complete summary of point types used in ***Axyz***.

Calibration

Calibration compares the output of one system or device against another much more accurate reference system or device in order to find corrections which will improve the accuracy of the less accurate system.

For example, measurements from a low accuracy Electronic Distance Meter (EDM) might be compared against corresponding values generated by a high accuracy interferometer. A table of corrections, or the parameters of a mathematical correction model, can then be calculated and used to correct further EDM measurements in a process of **error compensation**.

The objective of calibration is to reduce the effects of *systematic errors*. It cannot reduce the effects of *random errors*. To be effective, the reference system is normally 5 to 10 times more accurate than the system to be calibrated.

Strictly speaking, calibration involves the use of a reference device or system. However some "calibration" methods involve only internal measurements. For example, parameters which correct for the lack of alignment of *theodolite axes* can be calculated by measurements made purely by the theodolite itself. Similarly in *photogrammetry* the technique of **self-calibration** is often used.

Camera

Photo: INCA front view
Photo: INCA rear view

A camera is an optical device which enables the image created by a *lens* to be recorded on film or an electronic chip. It is a relatively complex device requiring additional mechanisms which can include:

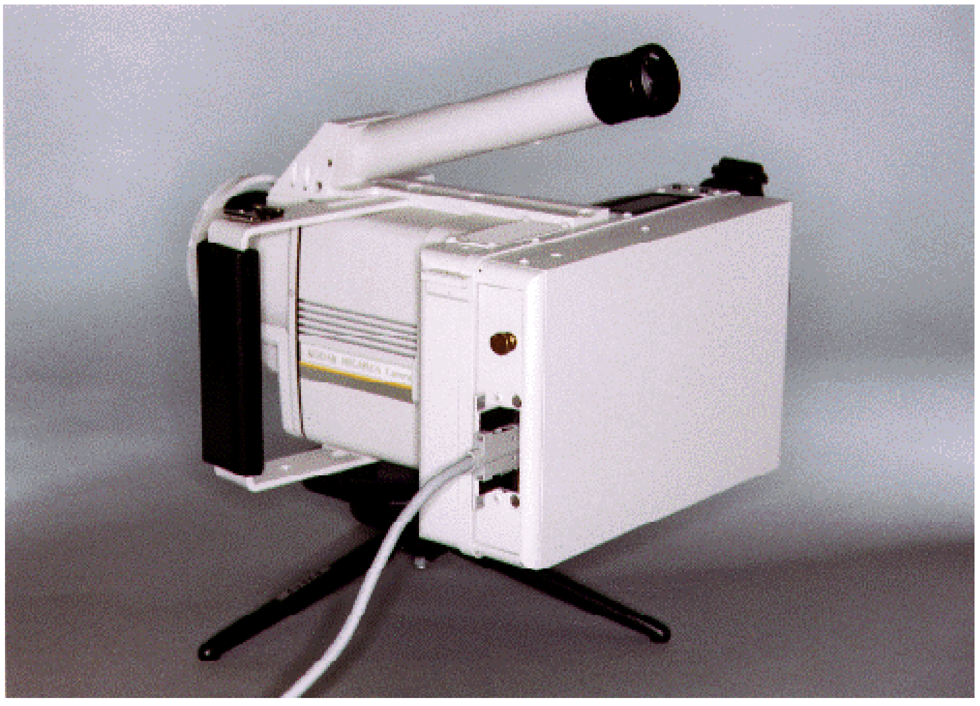
- Focusing mechanism to re-position the lens
- Exposure meter and shutter mechanism to admit the correct amount of light
- Viewfinder to manually check the image
- Film handling mechanism
- Electronic data acquisition and recording
- Flash illumination
- etc

For purposes of large scale metrology the camera defines directions to target points by mathematically re-projecting the image of the target back through the lens and into the object space. For good directional accuracy image positions must be known very accurately. Since these may be calculated to sub-micron levels, the stability and accuracy of the entire camera are critical.

Although good measurements can be made with standard cameras, such as those used by amateur and professional photographers, cameras specially designed for metrology, such as the INCA camera, will normally produce best results. These will have features such as rigid camera bodies and well defined focus positions. However even these cameras benefit from a process of *camera calibration* which can significantly reduce the effects of lens *aberrations* and uncertainties in the internal camera geometry.

Photo: INCA front view

Photo: INCA rear view



Camera calibration

Cameras are quite complex optical devices and they do not reproduce exact geometrical images from exact geometrical objects. For large scale metrology it would be convenient if they functioned like precisely manufactured *pinhole cameras*. Camera calibration enables an accurate mathematical model of the camera to be made. This model can then be used to correct measurements in the camera's image to equivalent image values from a pinhole camera.

Camera calibration aims to eliminate the effects of:

- *Aberrations* in the camera lens
- Errors in the image recording medium, such as distorted film or geometric defects in the electronic chip
- Uncertainties in the parameters defining the pinhole camera (**principal point** and **principal distance**)

Conventionally, camera calibration involves imaging some accurately known set of reference targets whose coordinates have been determined in some other way.

Alternatively, **self-calibration** avoids the use of reference targets and "calibrates" the cameras as part of the *orientation* procedure. The camera effectively calibrates itself. During orientation the parameters of the camera model are also included as unknown values, together with the position and tilt parameters of the camera stations. The solution then generates both camera model and relative camera location. The **camera parameters** defining the model may then be called the parameters of **interior orientation** to distinguish them from the 6 location and tilt parameters of **exterior orientation.**

Cateye

The Leica product name for a *cat's-eye* type of retro-reflector.

Cat's-eye

Diagram: Cat's-eye reflector
Photo: Cat's-eye in Birdbath
A type of *retro-reflector* constructed from two or more concentric glass spheres and hemi-spheres which are usually mounted in a spherical

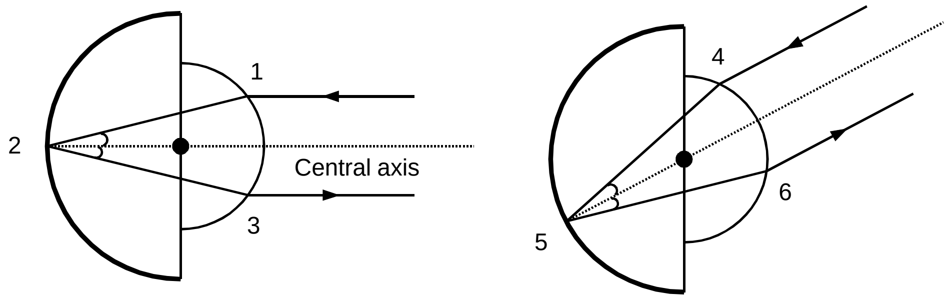
housing. The front surface is open to admit light, normally the laser beam from a *laser tracker*. The rear surface is silvered to reflect light.

Incoming light rays are refracted towards the centre of the spheres and reflect back off the rear surface. Reflection is symmetrical about the perpendicular to the spherical surface. This perpendicular is a radial line from the centre so the ray returns on the same direction but symmetrically offset about the centre. The offset is therefore twice the distance of the centre from the incoming ray.

The cat's eye has an *acceptance angle* of ±60°.

The diagram shows a simple cat's-eye made from two glass hemi-spheres of different diameter but with the same type of glass.

Diagram: Cat's-eye reflector



Cat's eye

Photo: Cat's-eye in Birdbath

CCD

Short for *Charge Coupled Device.*

CDM

Short for **Core Data Module**, one of the ***Axyz*** software modules.

Charge Coupled Device (CCD)

This is an electronic, solid state sensor which can record a photographic *image* as a 2-dimensional array of charges, rather than a varying deposit of silver, as in a conventional photograph.

The action of light on the sensor's surface generates electrical charges which depend on the local intensity of the image. Conductors on the surface set up "potential wells" (sensing elements) into which the charges from a local area flow and are held, until read out and recorded. Effectively, each well has averaged out the charge in its local area, thereby digitizing the image into an array of picture elements, commonly called **pixels**.

Currently, commercially available sensors (1998) have high *resolution* arrays of up to 3000 x 2000 pixels.

2-dimensional CCD arrays may also be called **area array** sensors to distinguish them from **linear array** sensors which only have a single line of sensing elements. To build up a 2D image a linear array must be scanned across the image. Electronic satellite images are likely to be based on linear arrays and the movement of the satellite itself provides the scanning action.

CMM

Short for *Coordinate Measuring Machine.*

Collar reflector

The collar reflector is a **prism retro-reflector** attached to the head of a *laser tracker*. It is used during initialization of the instrument to detect and eliminate any **beam offset error**.

Collimation

Collimate means to make parallel or bring into line.

In large scale metrology, collimation implies making pointings between two theodolites such that the line between their centres of rotation is established. This may also be called a **reciprocal pointing**.

Normally the centre of rotation of the theodolite being sighted cannot be directly marked with a target and an offset target somewhere on its telescope is used. Once a pointing has been made it is then necessary to *transit* the telescopes and repeat the process. These two pointings are symmetrically located about the required line between centres.

Control point

Control points are *reference points* which are used exclusively to modify or "control" the effects of an *orientation* procedure during the phase of *bundle adjustment*.

Control points represent fixed information which is included in the adjustment. This can be done by giving them high *weights* so that their values do not significantly change. Instead, other values such as station locations must change to be compatible with the control. Control points are therefore frequently used to created orientations which have a coordinate system based in the object.

Sometimes not all coordinate values of a control point are known. For example, the design values may only be specified for the XY plane. These locations may be known as **partial control points**.

See *point* for a complete summary of point types used in ***Axyz***.

Coordinate Measuring Machine (CMM)

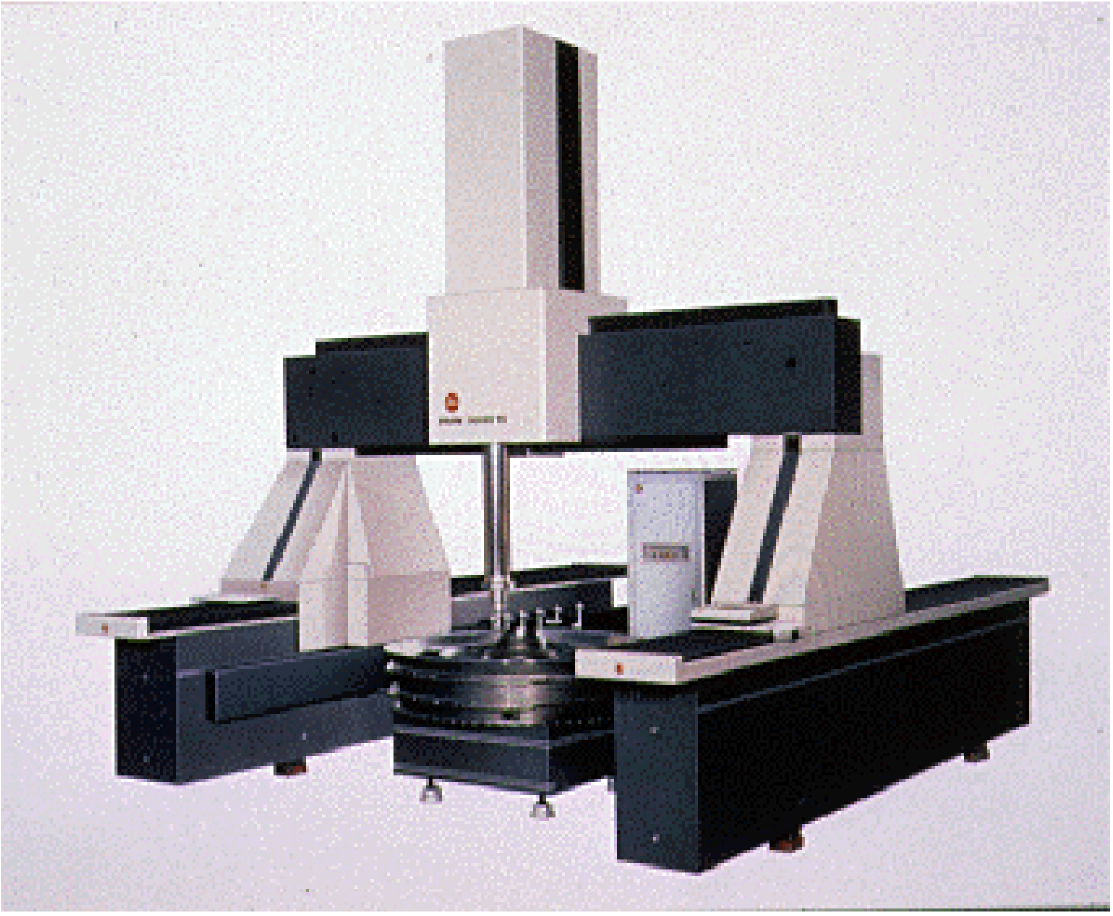
Photo: Coordinate Measuring Machine
This machine incorporates a probe which can be slid along 3 physically defined and mutually perpendicular axes. An object to be measured is placed on the machine. The probe is often a mechanical **touch probe**, typically incorporating a ruby sphere. By touching this against the object the current contact position of the probe defines a point on the object.

Encoders on the slides enable the probe position to be recorded, each encoder providing one of the 3 coordinate elements of position.

The measurement volume of a CMM is restricted by the length of the slides. CMMs with slide lengths of several metres would be regarded as large. They are constructed of heavy, stable materials and typically housed in a climatically controlled environment. Measured objects are therefore brought to the machine.

Accuracies can be very high, of the order of a few microns or better. This is partly achieved by comprehensive calibration of the measuring volume. The probe itself is also a sophisticated measuring device. The touch probe, also called a **touch trigger probe,** is very sensitive to surface contact but a non-contacting **optical probe** is also possible.

Photo: Coordinate Measuring Machine



Coordinate system

Diagram: Right and left handed systems
Principle: Right and left handed systems
A coordinate system is a set of 2 or 3 intersecting *axes*. Normally these are mutually perpendicular or *orthogonal*. Two axes are required to define planar objects and three for spatial objects. The *coordinates* of a point are defined with respect to these axes.

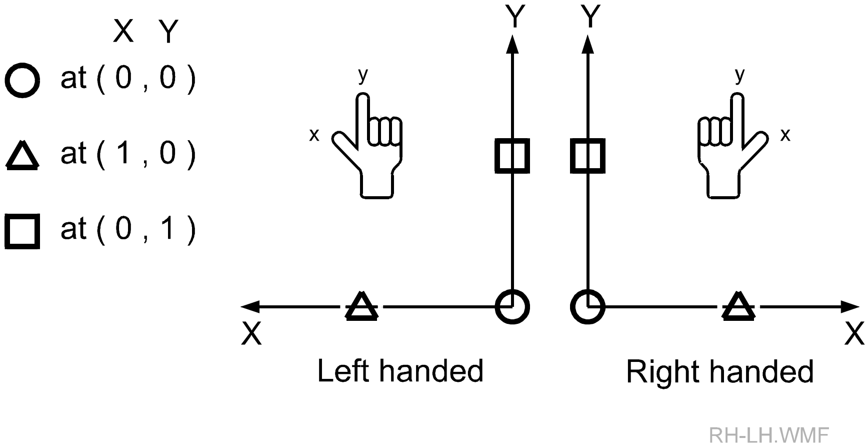
The intersection point of the axes is the **origin** of the coordinate system.

There are two possible arrangements of the axes, one being a **mirror image** of the other. These are known as **right handed systems** and **left handed systems** and are illustrated in the diagrams.

Axyz can handle multiple 3D coordinate systems. These are defined by the parameters of a *7-parameter transformation* with respect to the *Base coordinate system*. At any time, one of the coordinate systems is the **active coordinate system** and this is used as the default system for the display of coordinates. It may be changed to one of the other systems at any time.

Alternatives:
Reference system
Coordinate frame of reference

Diagram: Right and left handed systems



Principle: Right and left handed systems

The order in which axes are defined is important. A simple 2D case illustrates the point.

If axes are defined in an order X then Y, the set of coordinates defining a point are assumed to correspond to this order. For example, a point with coordinates (3.8,4.5) has X value = 3.8 and Y value = 4.5. However, the axes can be physically drawn in two different ways and the shapes form a different pattern in each. One pattern is a mirror image of the other.

Your hands provide a simple way to remember the arrangement. With palms up and thumb and forefinger of the left and right hands extended as shown, they point in the positive directions of the first and second axes respectively (here called X and Y). If the third finger is extended upwards, it will point in the positive direction of the third axis of a 3D system (typically called Z).

Coordinates

Cartesian coordinates
Rectangular coordinates
Spherical coordinates
Cylindrical coordinates

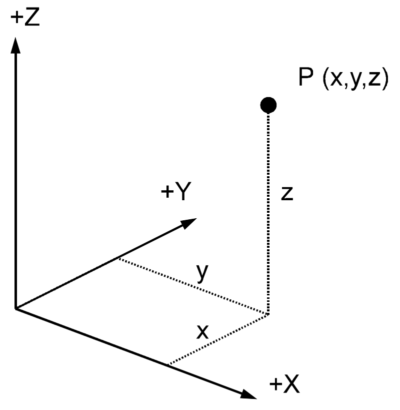
Coordinates are a means of representing points in 2D and 3D space by defining its position within a particular *coordinate system* formed by a fixed pair or triplet of axes.

Typically a point is located by measuring its distance along each axis from the origin of the coordinate system, which is where the axes intersect. Other types of coordinate are possible but in 3D space, for example, 3 values are normally required to define a point. This triplet of numbers is the point's coordinates.

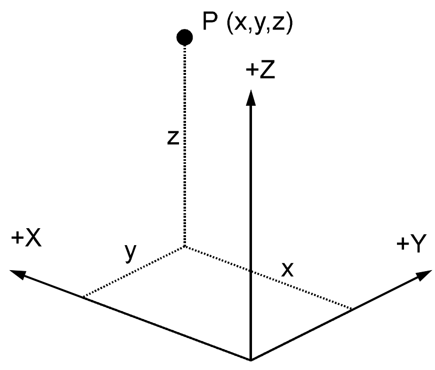
Cartesian coordinates

An alternative name for rectangular coordinates. Named after the French mathematician René Descartes.

Rectangular coordinates

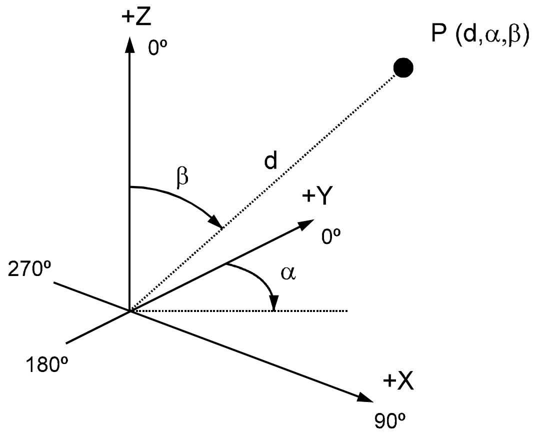


Right-handed Cartesian (rectangular)
AXREC-R.WMF



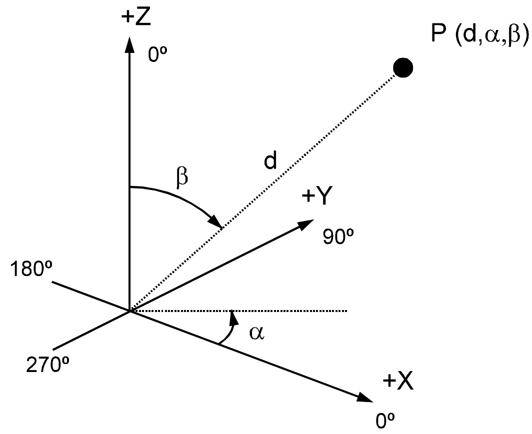
Left-handed Cartesian (rectangular)
AXREC-L.WMF

Spherical coordinates



Spherical clockwise

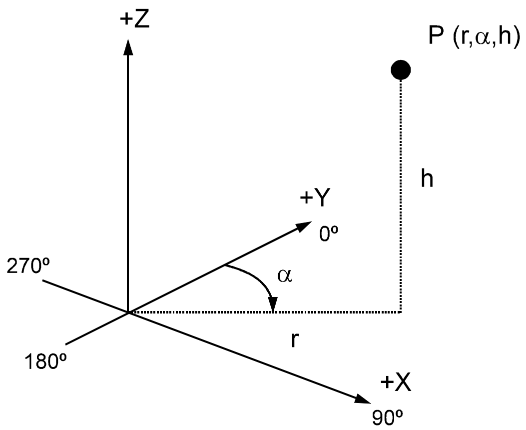
AXSPH-C.WMF



Spherical counter clockwise

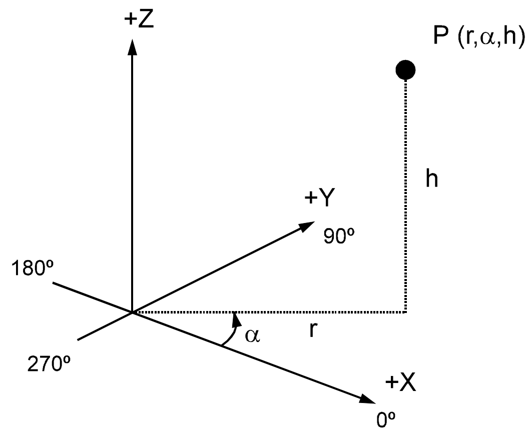
AXSPH-A.WMF

Cylindrical coordinates



Cylindrical clockwise

AXCYL-C.WMF



Cylindrical counter clockwise

AXCYL-A.WMF

Corner cube

Diagram: Hollow corner cube
Photo: Corner Cube Reflector
Photo: Tooling Ball Reflector (TBR) and accessories
Diagram: Maths of corner cube reflection
Maths: Corner cube reflection

A type of *retro-reflector* constructed from 3 plane mirrors at right angles to each other. It is typically used to reflect laser beams from a *laser tracker* or *EDM* beams from a *Total Station.* For industrial use it is often mounted in a spherical housing.

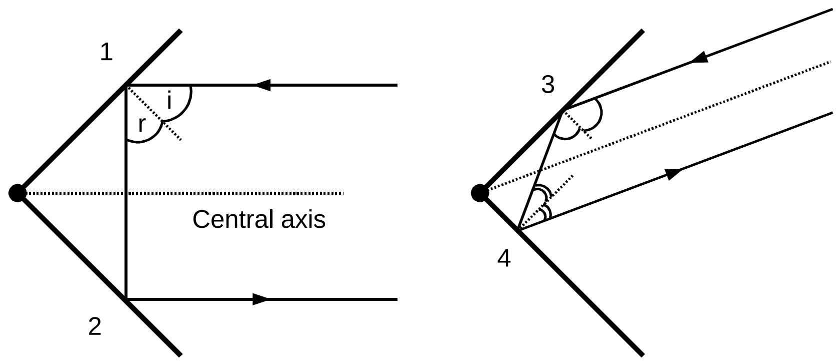
If the mirror arrangement is based on 3 individual plane mirrors the device is known as an **air-path corner cube** or a **hollow corner cube.**

A hollow corner cube has an *acceptance angle* of ±20°.

If the mirrors are created by grinding and silvering 3 smooth surfaces on a glass block, the device is known as **prism retro-reflector**. This is the critical element in a **tooling ball reflector (TBR)** which is only a few millimetres in diameter and has a much wider acceptance angle of ±60°. The hollow corner cube has a target point fixed at the intersection of the mirror surfaces. A prism retro-reflector is affected by *refraction* and the target point varies slightly, depending on the angle at which the incoming rays enter the reflector. Distances measured by EDM or ADM will also be slightly affected by refraction.

The diagram shows a hollow corner cube in two dimensions, in order to demonstrate the principle. The incident angle (i) of an incoming light ray equals the angle of reflection (r) at the mirror surface. If the ray is traced through the device the returning beam is parallel to the incoming beam but symmetrically offset with respect to the apex of the mirrors. The offset is therefore twice the distance of the apex from the incoming ray.

Diagram: Hollow corner cube



Corner cube

Photo: Corner Cube Reflector

Photo: Tooling Ball Reflector (TBR) and accessories

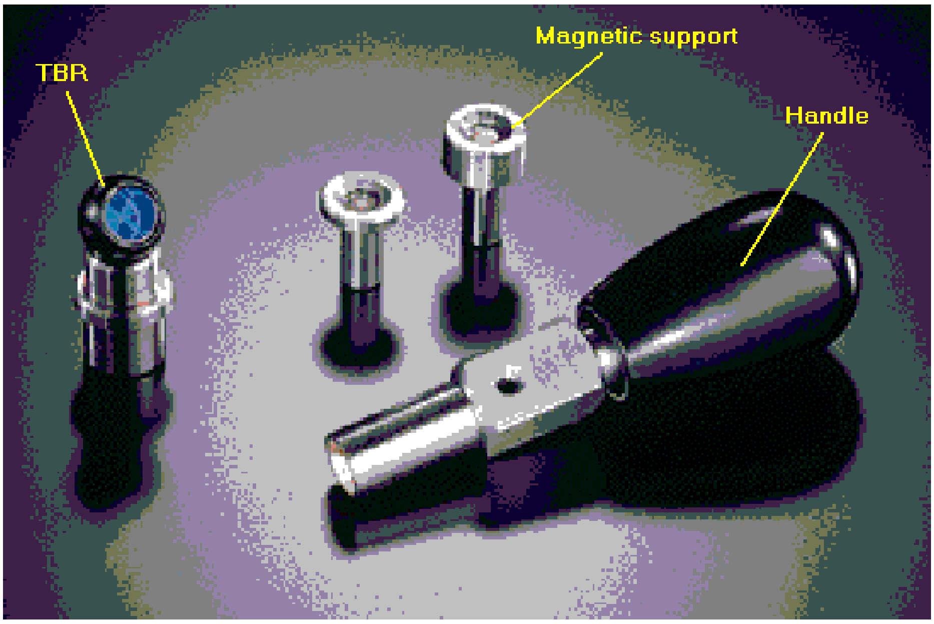
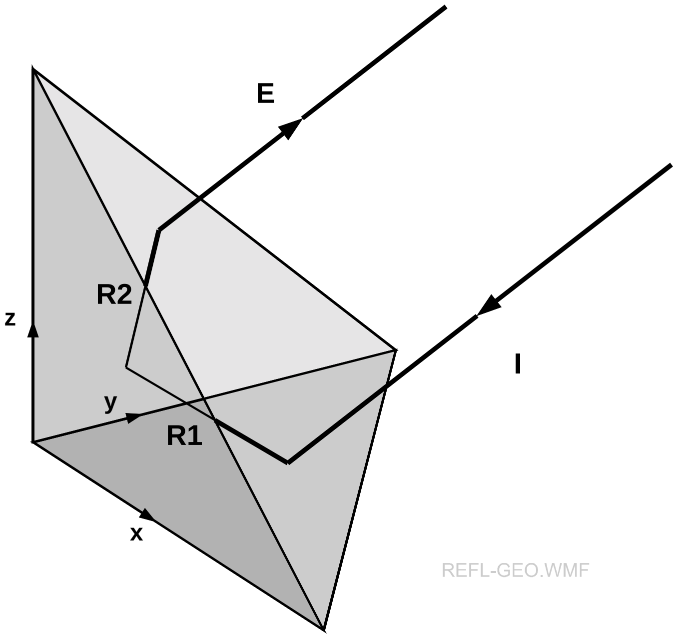


Diagram: Maths of corner cube reflection



Maths: Corner cube reflection

Vector geometry shows that the emergent ray E is parallel to the incident (incoming) ray I. It is simplest to define a local coordinate system along the edges of the corner cube as shown. The geometry is independent of the actual coordinate system.

The diagram shows 3 reflections on each face of the corner cube. The argument assumes a second reflection on the xz plane but an equivalent argument applies if the second reflection is on the yz plane.
The incoming ray **I** is reflected on the xy plane along **R1**.
R1 is reflected on the xz plane along **R2**.
R2 is reflected on the yz plane to produce the emergent ray **E**.

The general equation for a reflected ray **R**, given an incident ray **I** and mirror normal vector **N** is:

$\mathbf{R} = \mathbf{I} - 2\,(\mathbf{I} \cdot \mathbf{N})\,\mathbf{N}$ (see "Reflection" on page 97)

Normal for xy plane: $\mathbf{N_{xy}} = (0, 0, 1)$
Normal for xz plane: $\mathbf{N_{xz}} = (0, 1, 0)$
Normal for yz plane: $\mathbf{N_{yz}} = (1, 0, 0)$

Let the incident ray be a general vector **(l, m, n)**.

$$\mathbf{R1} = \mathbf{I} - 2\,(\mathbf{I} \cdot \mathbf{N_{xy}})\,\mathbf{N_{xy}} = (l, m, n) - 2\,(n)\,(0, 0, 1) = (l, m, -n)$$

R2 = R1 – 2 **(I . Nxz) Nxz = (l, m, -n)** – 2 (m) **(0, 1, 0) = (l, -m, -n)**

E = R2 – 2 **(I . Nyz) Nyz = (l, -m, -n)** – 2 (l) **(1, 0, 0) = (-l, -m, -n)**

i.e. **E = -I** (emergent ray is parallel to incident ray an in opposite direction)

Correlation

Correlation is the interdependence of two variables, such as the measured X coordinate and the measured Y coordinate of a particular target. It is quantified by the *covariance* of the errors associated with the variables.

All measured quantities are subject to *random errors* which are usually independent of each other. The random error in pointing at target A is not normally affected by the random error in pointing at target B.

Some measurements are not made directly but are derived entirely from others. For example, a target can be intersected from two theodolites to generate its X,Y and Z coordinates. Errors in each coordinate value, E_X, E_Y and E_Z, are based on the angular errors of the two pointings. Although the individual coordinate errors are different because a different function is used to compute each one, they will be related or correlated since they all use the same starting information, i.e. the same errors in the same two pointings.
Errors which are not independent but related in some way are known as **correlated errors**.

Covariance

Covariance is a measure of the *correlation* between the errors associated with any two measurements. It is defined in an analogous way to the *variance* of the errors associated with one of the measurements. (In fact, variance can be viewed as the covariance of a measurement with itself.)

Suppose the two measurements A and B are repeated N times, generating two sets of deviations from mean values, a_i and b_i. Using the standard symbol σ_{ab} for the covariance between A and B:

$$\sigma_{ab} = \sum_{i=1}^{N} \frac{a_i \cdot b_i}{N} \qquad \text{or} \qquad \sigma_{ab} = \frac{a_1 \cdot b_1 + a_2 \cdot b_2 + .. + a_N \cdot b_N}{N}$$

Note that σ_{ba} will clearly be the same as σ_{ab}.

If the measurements are uncorrelated they will randomly have positive and negative values. The individual product terms will therefore also be sometimes positive and negative and the covariance will tend to average out to zero.

However if a positive error in A tends to be associated with a positive error in B, then the covariance will tend to be positive. The same applies if a negative error in A correlates with a negative error in B. The signs can also go in opposite directions, which would result in a negative covariance.

Covariance matrix

The covariance *matrix* summarizes the variances and covariances between a set of measurements. These can be mixed types such as angles and distances or the same types such as coordinate values.

The matrix is a by-product of many analytical procedures in large-scale metrology, such as a *bundle adjustment*, and a necessary requirement for others, such as *error propagation*.

For N measurements, the matrix has N x N elements. The diagonal elements are the variances of the measurements and the off-diagonal elements are the covariance values between pairs of measurements.

$$\begin{vmatrix} (\sigma_1)^2 & \sigma_{12} & .. & .. \\ \sigma_{21} & (\sigma_2)^2 & .. & .. \\ .. & .. & .. & .. \\ .. & .. & .. & (\sigma_N)^2 \end{vmatrix}$$

Alternatives:
variance/covariance matrix
dispersion matrix

Cover plate

On a *laser tracker* the cover plate is parallel sided glass plate through which the laser beam exits onto the mirror in the tracking head.

CS

Short for *Coordinate System.*

D

Database

A logically organized collection of data with the following principal properties:
1. Data can be added, deleted or modified
2. Data need not be all of the same type and multiple data types are typical
3. Data can be accessed and presented in different ways
4. Data may be extracted for processing according to different criteria

Each *job file* in ***Axyz*** is a database. The database design has been developed using Microsoft ACCESS ™. It is essentially a set of tables, each recording data of a particular type, e.g.

- Parameters relating to a station's definition and orientation
- Measurements made at a particular station
- Definition of units of measurement
- etc.

DD

Short for Decimal Degrees.

Degrees of freedom

Diagram: Roll, pitch and yaw
1) Mechanical and spatial
The number of spatial and dimensional parameters needed to describe an element's location, angular attitude and size in space.

In 3D space a point has 3 degrees of freedom, one for each coordinate value required to locate it.

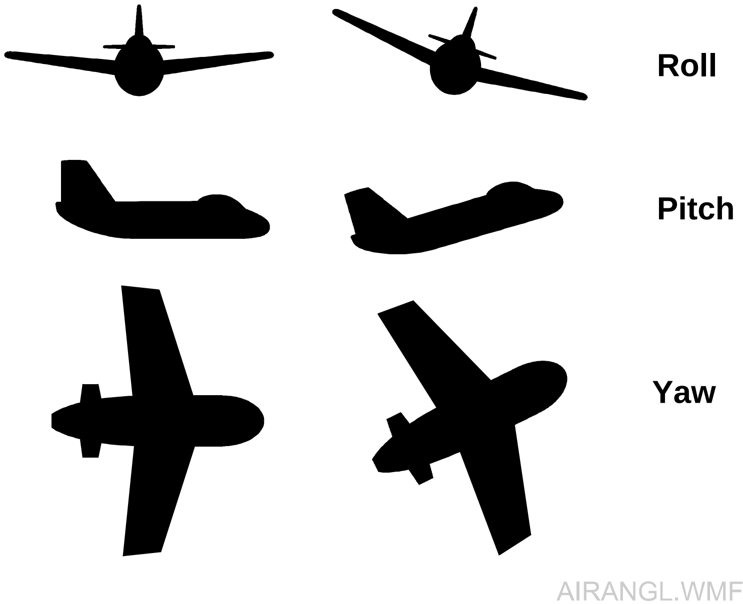
An object such as an aircraft has 6 degrees of freedom. 3 relate to coordinate values for position and 3 relate to angular attitude. For an aircraft these are typically known as the angles of **roll**, **pitch** and **yaw**.

In metrology it may also be necessary to allow for scale changes due, for example, to thermal effects. In 3D space this implies a 7th. degree of freedom.

2) Statistical

An alternative name for *redundancy*.

Diagram: Roll, pitch and yaw



Depression angle

The absolute (positive) value of a negative *vertical angle.*

The angle from the horizontal plane through a measuring point to a target below the plane.

Device point

One of the targets on a *hidden point device.* The device points are offset from the hidden point and are the actual targets sighted by the instruments.

Each device point has its own positive integer **device point number** which uniquely identifies it on the hidden point device. The number for the hidden point itself is zero.

For consistency within the *job file,* all directly measured points are also assigned the device point number zero.

See *point* for a complete summary of point types used in ***Axyz***.

Alternatives:
Offset target

Diode

A solid-state electronic device made of semi-conducting material and permitting current flow in one direction only.

Dispersion

<u>1) Optics</u>
The separation of white light into its component colours by an optical element such as a glass prism. This is due to a variation in refractive index. See *refraction***.**

<u>2) Statistics</u>
The extent to which values of some measured quantity vary. See *variance*.

DM

Short for **Data Manager**, one of the ***Axyz*** software modules.

Dongle

A dongle is an electronic device which protects against unauthorized use of a software package.

The ***Axyz*** system uses a dongle which plugs into to the *parallel port* of the controlling computer. The ***Axyz*** software checks for the presence of the dongle, which also stores the codes authorizing use of a particular software module. The module will not run if the dongle is not present or the correct code is not enabled.

E

ECDS

Short for Electronic Coordinate Determination System.
This was one of Leica's earlier 3D coordinate systems based on theodolites. It was manufactured by *Kern* Swiss.

EDM

Short for *Electromagnetic Distance Measurement*, **Electronic Distance Meter**

Electromagnetic Distance Measurement (EDM)

This principle is used by the distance measuring components of *Total Stations*. Typically an infra-red beam is transmitted from the Total Station to a *retro-reflector* from where it returns to the instrument. By measuring back at the transmitting device, the calculated distance is actually twice the value required.

There are two techniques which may be used to calculate the distance

1. **Phase measurement**
   The beam may be *amplitude modulated (AM)*. The *phase* of the transmitted and returned modulations can be compared and this enables the fractional component of the distance to be calculated. By making measurements at 2 or more frequencies the whole part of the distance can also be derived.
2. **Time-of-flight**
   The beam may be pulsed. The time taken for the pulse to travel to the reflector and back can be recorded. Knowing the speed of light the distance can be calculated.

Elevation angle

A positive *vertical angle*.

The angle from the horizontal plane through a measuring point to a target point <u>above</u> the plane.

Engineer

Someone who can do for a dime what any !#*% fool can do for a dollar.

Enhanced Reference System (ERS)

In the aerospace industries this is an existing system of *reference coordinates* which has been extended or "enhanced" with additional reference points.

Typically existing reference points exist only on the manufactured component, tool or jig which is being built or inspected. In confined environments these points may not be conveniently accessible to optical metrology systems which rely on lines of sight. Additional reference points, typically created off the object make it faster and easier to use the measurement systems.

Entered point

A point in the job file which is input manually or imported from an external file.

This type of point provides a general purpose facility for checks and calculations.

See *point* for a complete summary of point types used in ***Axyz***.

Error

An error is the difference between the true value of a measurement and what you actually measure. Errors have 3 basic sources:

- Small random variations (a fact of life beyond anyone's control)
- Systematic effects (can be compensated by suitable modelling methods)
- Mistakes (can often be detected by check procedures)

Error budget

In most measurement procedures *errors* accumulate due to a chain of measurement steps. For example, instruments may first be located with respect to some standard fixed reference points, then further target points located from the instruments. In this case errors are associated with the following steps:

- Establishing the reference points
- Locating instruments by measurements to these points
- Locating the target points

The final target point errors are an accumulation of these errors. In designing a suitable measurement procedure for locating targets you may define a total **error budget** which you divide up between the various critical stages.

Error propagation

Error propagation answers questions such as:

> "If my angles are good to 0.7" and distances good to 2 microns, how good are the measured point coordinates?"

> "If my point coordinates have standard errors of 50 microns, how good is the radius of the fitted circle?"

Error propagation is an analytical technique which carries through the effects of an error source in a sequence of calculations. In large-scale metrology the technique provides *variance* and *covariance* values of elements which ultimately depend on original measurements and their error sources. Its accuracy depends directly on accurate estimation of these. For example, if pointing errors are assumed to be more accurate than in reality, then this technique will give resulting coordinates an accuracy which is also too high.

ERS

Short for *Enhanced Reference System.*

F

Far point

The measured target on a *hidden point rod* which is furthest from the tip (the actual hidden point).

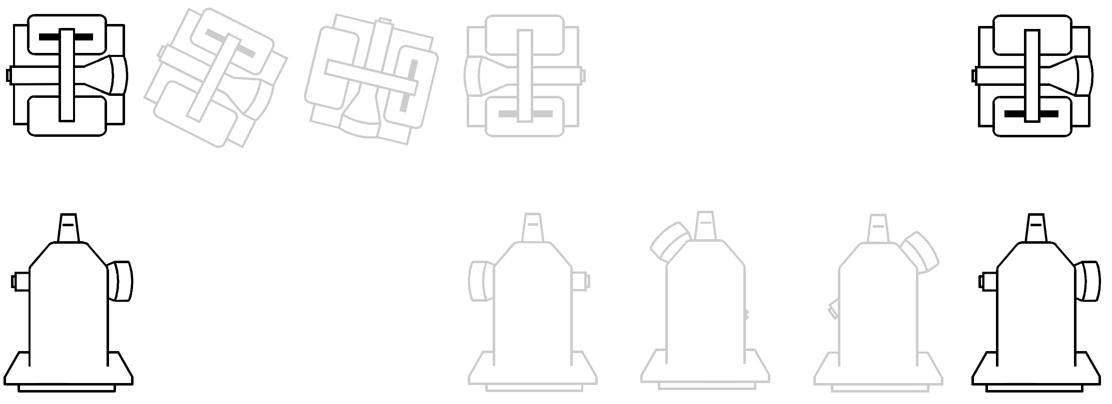
Face

Diagram: Change face

The telescopes on theodolites and Total Stations, and the mirror on a laser tracker, can be pointed at a target in two ways. From one position the instrument can be rotated about the standing axis (vertical axis) by 180°. The telescope or mirror can then be rotated about the transit axis (horizontal axis) to point again at the target.

"Face" refers to the face (plane) of the vertical circle (encoder). From a position behind the telescope eyepiece and sighting the target, this face will be on the right hand side or left hand side, depending on the way the pointing is made. The terms **face left** and **face right** are used to distinguish between the positions. The term **change face** means to move from one of these positions to the other.

Diagram: Change face



CHNGFACE.WMF

Fiducial mark

Target points on an image are measured in a local 2D *coordinate system*. These image coordinates must ultimately be located in the 3D coordinate system defined by the camera which took the image. (See the simple *pinhole camera* which shows how image coordinates are combined with the camera's projection centre to define a 3D direction in space.)

In conventional film cameras the image is measured outside the camera and there is no immediate connection between the coordinate system of the film measuring device and the coordinate system in the camera. Some cameras are therefore provided with marks on the edges of the film plane which are exposed onto every image. These **fiducial marks** have known coordinates within the camera's coordinate system, thereby enabling coordinates measured by a third system to be converted to coordinates in the camera's system. A common and simple arrangement has 4 marks on the centres of the image sides. The lines joining the left/right and top/bottom marks define the x and y axes in the image and camera.

As an alternative, cameras may have a glass plate in the image plane with a complete array of fine crosses etched across it. This is known as a **reseau plate** and it not only serves to keep the film flat but provides multiple reference points across the image. Like fiducial marks these can also be used both to locate the camera's coordinate system and, in addition, can help correct for distortions such as film stretching.

In electronic cameras the recording chip essentially has a known location with respect to the camera body and the relative location of every **pixel** is accurately known.. Fiducial marks and reseau crosses are not therefore required in this case.

In metrology, fiducial marks (or chip parameters) can only help to provide a good estimate of target directions. *Camera calibration* will still be required to achieve the highest levels of accuracy.

Field check

A quick measurement designed to check that a measuring system is functioning properly. Different types of field check can be made. A common check is a **2-face check (two face check)** in which pointings or measurements are made in both *faces* to one or more fixed targets. If the instrument is accurate, angle differences between faces should be zero, except for random pointing error.

Trackers can also make the following checks:

1. **Ball bar check**
   Measurements to a Ball bar target should all lie on a circle.
2. **IFM check**
   Also called a **Home point check** or **Birdbath check**. This checks if the current value of the *Birdbath distance* is correct.

3. **ADM check**
   Measurements to fixed points using ADM and IFM should give the same distance in each case.

FM

Short for *Frequency Modulation*, Frequency Modulated.

Free net adjustment

This is a variation of a *bundle adjustment* which optimizes a network orientation in such a way that the estimated errors in locations and orientation parameters are more evenly distributed.

In a more conventional technique certain parameters are held fixed, such as the location and angular attitude of the first station in the network. This station is then assigned zero error and all other errors are computed relative to it. The free net technique simply avoids giving preference to any one instrument for purposes of error estimation but does not alter the shape of the network.

Frequency modulation (FM)

Electromagnetic signals (light beams or radio waves) used to make measurements or carry information are build up from sine waves of known frequency.

The frequency may be modulated in a sinusoidal way. The wavelength of the modulation is much larger than the wavelength of the underlying **carrier signal**.

The component of the beam which represents the frequency modulation may be used to measure distance.

As an alternative to modulating the frequency, the carrier signal may be *amplitude modulated*.

G

Gaugeless manufacture

The manufacture of objects such as aircraft and automobile components without the use of a *master gauge*.

Alternatives:
jigless manufacture
jigless assembly

Greek characters

The following Greek characters are commonly used in ***Axyz*** documentation:

Character	Usage
σ	sigma - standard error
$σ^2$	sigma squared - *variance*
β	beta, for beta-testing
δ	delta, a small difference
Ω,ω	omega - rotation about X axis
Φ,φ	phi - rotation about Y axis
Κ,κ	kappa - rotation about Z axis

GSI

Short for Geodetic Services, Inc.

Manufacturers of software and hardware for industrial *photogrammetry*. The company is based in Melbourne, Florida, USA.

H

Horizontal angle

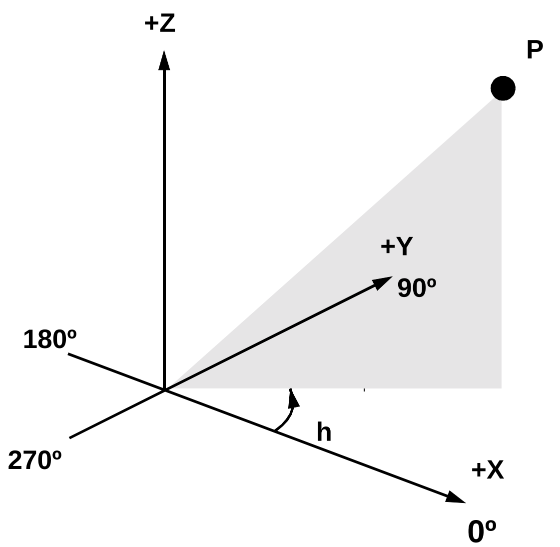
Diagram: Horizontal angle

An angle measured in the horizontal plane. In a conventional right handed coordinate system (X,Y,Z) where X and Y are the axes in the horizontal plane and Z is the vertical axis, the angle is measured positively from the X axis towards the Y axis.

This is the definition used in mathematical texts and analyses. Sometimes it is loosely used to refer to the *azimuth angle* which is the angle measured on the **horizontal circle** of theodolites, Total Stations and laser trackers.

The term is also commonly used even if the instrument is only approximately levelled.

Diagram: Horizontal angle



Horizontal angle, h

ANGL-HOR.WMF

Hidden point

This is the actual target point on a *hidden point device* which cannot be directly sighted.

See *point* for a complete summary of point types used in ***Axyz***.

Alternatives:
Tip

Hidden point device

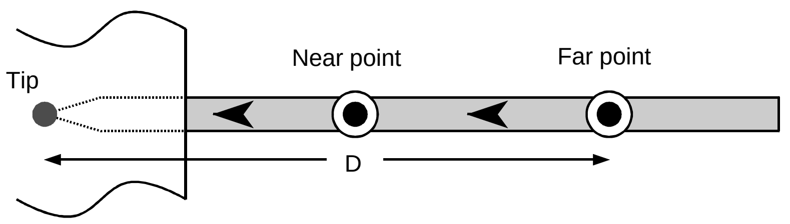
Simple hidden point rod
Multi-target hidden point rod
Multi-target hidden point frame
Photo: Hidden point rod and vacuum support

A general term for a multi-targeted device used to locate points which are not directly visible from some instrument stations. It has a tip which is touched against the required point and a number of offset targets which can then be seen. The dimensional relationship between tip and offset targets is known so that when coordinates for two or three offset targets have been generated, the tip coordinates can be derived.

Different designs of hidden point device are possible.

See also *sine bar*.

Simple hidden point rod

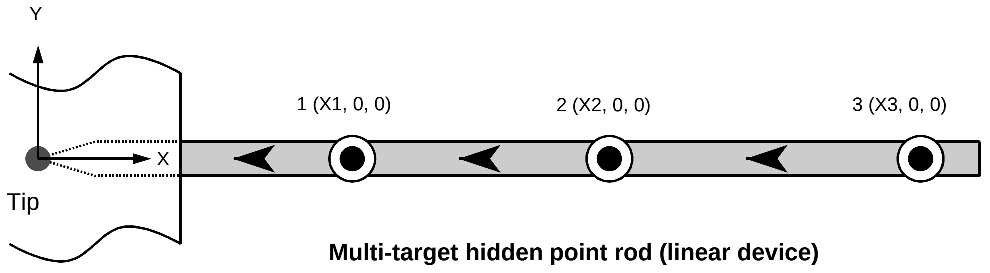


Simple hidden point rod (linear device)

HIDPT-A.WMF

This is a linear device with two offset targets which lie on a straight line with the tip. When far point and near point have been measured a vector can be calculated from the far point towards the near point with a known length D. This vector then locates the tip or hidden point.

Multi-target hidden point rod

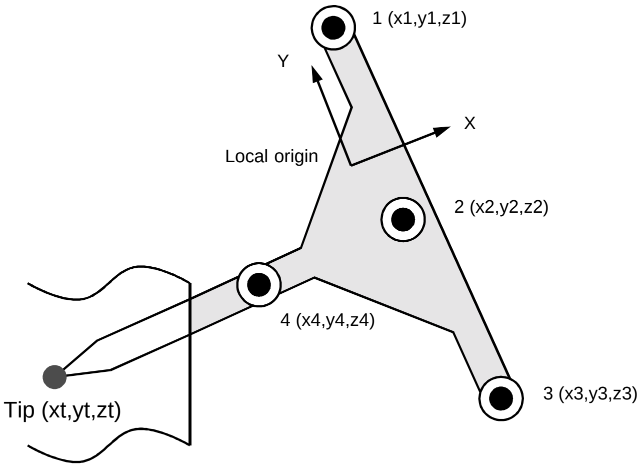


Multi-target hidden point rod (linear device)

HIDPT-B.WMF

This is a linear device with two or more offset targets lying on a straight line with the tip. The targets are a known distance from the tip. When any two targets have been measured they define the direction to the target. Taking the distance to either target locates the tip or hidden point along this direction.

Multi-target hidden point frame

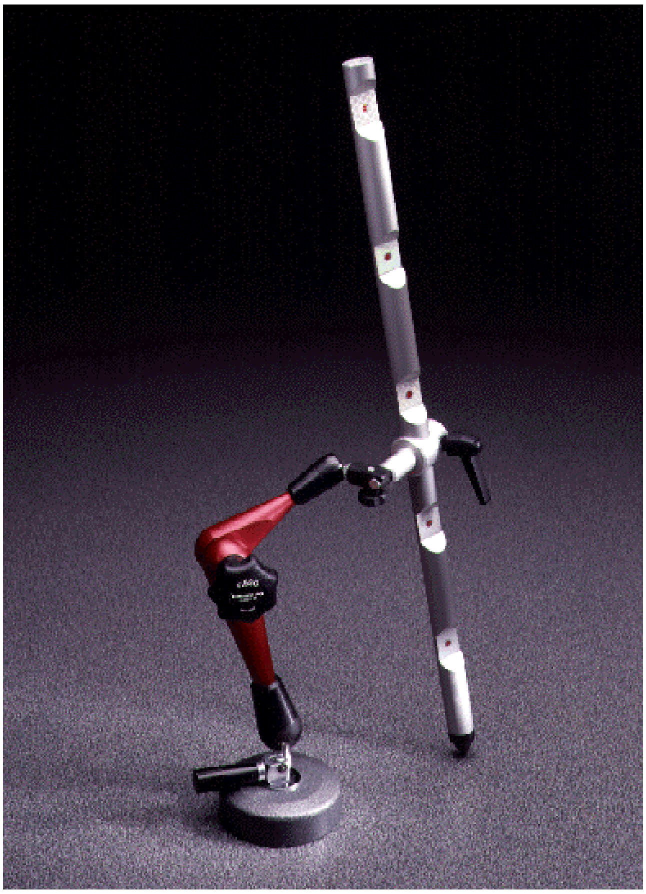


Multi-target hidden point frame (non-linear device)

HIDPT-C.WMF

This is a non-linear device in which the tip or hidden point and 3 or more additional targets have coordinates in a *local coordinate system*. Provided 3 targets are measured which do not lie on a straight line, the coordinates of the tip can be deduced by a *3D transformation* procedure.

Photo: Hidden point rod and vacuum support



Hz

Short for Hertz.
International symbol for frequency, meaning "cycles per second".
Named after the German physicist, Heinrich Rudolf Hertz.

I

ID

Short for Identifier.
A string of alpha-numeric characters which identify or name a particular item of data.

IFM

Short for *Interferometer*.

Image

An optical reproduction of an object formed by some arrangement of mirrors and/or *lenses*.

A **virtual image** is one which cannot be projected onto a surface. The image of an object in a plane mirror is an example.

A **real image** is one which can be projected onto a surface. A *camera* typically creates such an image, also called a **photographic image** if recorded on conventional photographic film or called an **electronic image** if recorded by an electronic chip such as a *Charge Coupled Device*.

An electronic image is also called a **digital image** or **digitized image**. Photographic images can be converted to digitized images by a diverse range of electronic devices such as flatbed scanners. In digitized form images can be subject to a wide range of **image processing** methods with which they can be mathematically manipulated and analyzed to extract specific data such as a target's imaged position.

The term **video image** usually implies a dynamic sequence of images which can give the impression of movement, as in a television transmission. A **still image** is a single image considered in isolation. It may be taken by a camera or extracted from a video sequence.

Inspect

To check critical points on an object against their reference coordinates.

INCA

Short for INtelligent CAmera.

This digital camera is manufactured by Geodetic Services, Inc. and has its own computer for on-board **image processing**.

See also *camera*.

Instrument axes

Diagram: Theodolite axes
Diagram: Tracker axes
The instrument axes indicate reference directions and axes of rotation for theodolites, Total Stations and laser trackers.

All three classes of instrument are designed to be positioned such that the **primary axis** of rotation is approximately vertical. This primary axis is also called the **standing axis** or **vertical axis**. Rotations around this axis indicate the horizontal angle.

The telescope or mirror is further rotated about a **secondary axis** of rotation, also known as the **transit axis** or **trunnion axis** or **horizontal axis**. A rotation about this axis is indicated by a change of vertical angle.

The actual pointing to a target is indicated by the **line-of-sight** along the **telescope axis** or by the **laser beam axis**.

A rotation about the standing axis sweeps the secondary axis in an approximately horizontal plane.

A rotation about the transit axis sweeps the line-of-sight or laser beam in an approximately vertical plane.

In perfect instruments the axes are exactly aligned:
- The transit axis is perpendicular to the standing axis
- The telescope axis is perpendicular to the transit axis
- Before reflection the laser beam axis is identical to the standing axis.
- After reflection the laser beam axis is perpendicular to the transit axis

In real instruments this is never the case. For optimal accuracy instrument readings must be corrected following a process of *calibration* or *alignment.*

Diagram: Theodolite axes

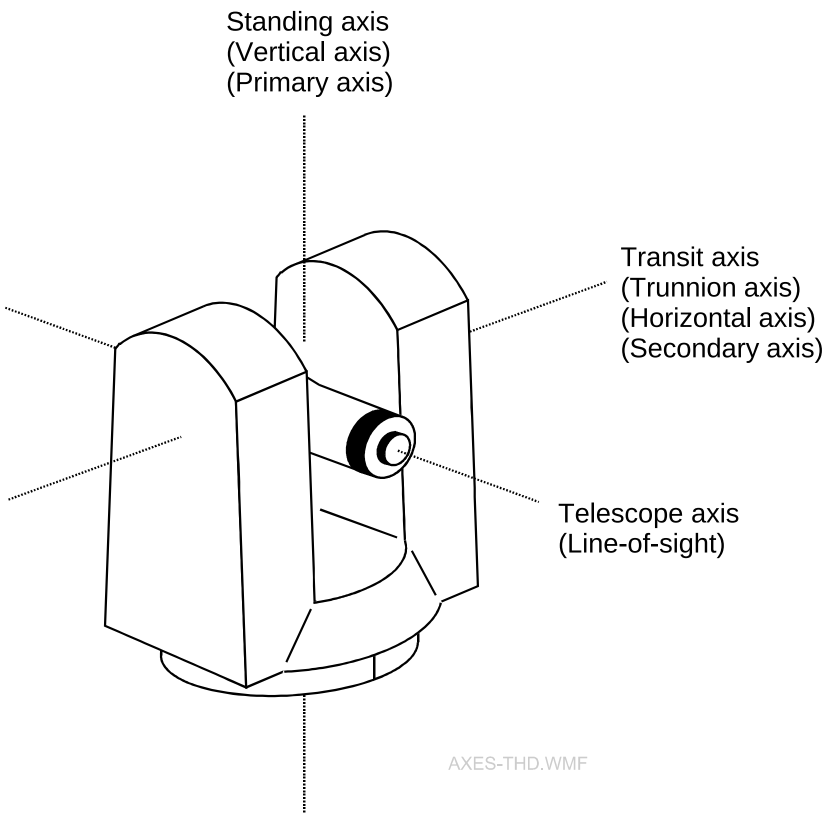
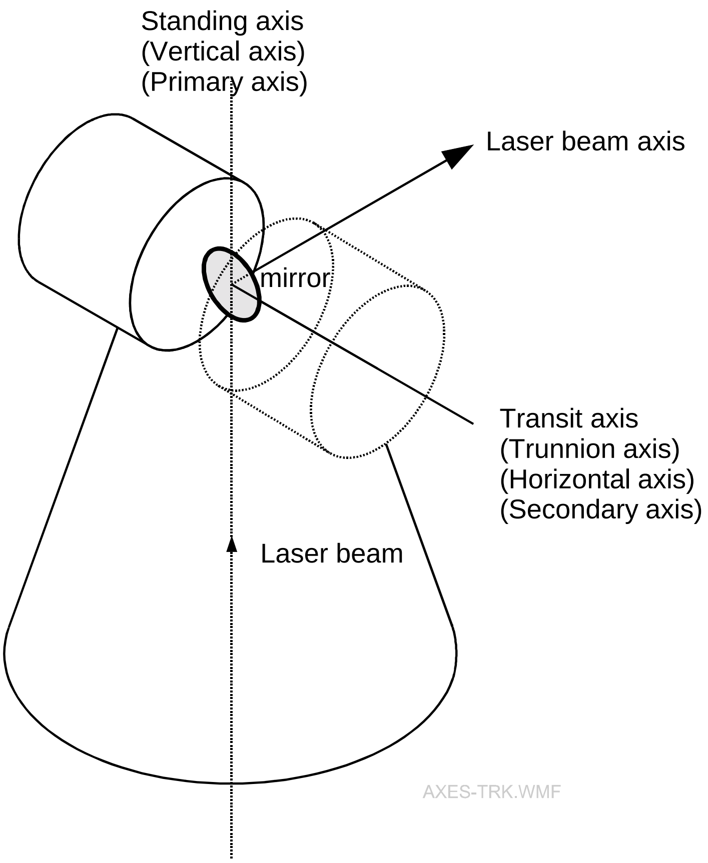


Diagram: Tracker axes



Instrument coordinate system

Photo: Tracker coordinate system

An instrument *coordinate system* is the arrangement of origin and axes defined by a theodolite, Total Station or laser tracker.

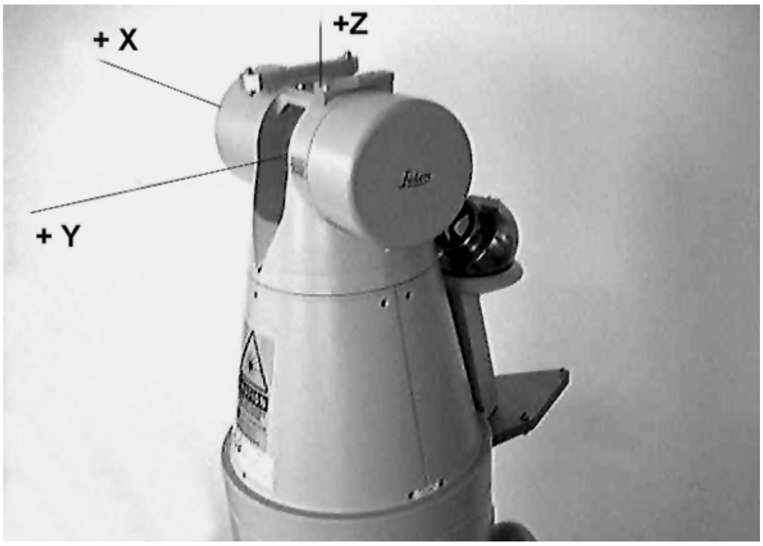
The origin is always at the intersection of the *instrument axes*.

The axes form a **right handed system** as follows:

- y axis on horizontal zero
- x axis on horizontal 90°
- z axis points vertically up when the xy plane is horizontal (i.e. when the instrument is levelled). (The standing axis represents the z axis.)

Angles are normally displayed on theodolites and Total Stations and so the x and y directions are readily determined. On a laser tracker this is not the case but the position of the *Birdbath* provides a reference orientation in the xy plane. Here the direction of the negative Y axis is from the mirror towards the Birdbath. The photo shows the positive Y axis, which therefore points away from the Birdbath.

Photo: Tracker coordinate system



Instrument coordinates

When a new tracker station is added to a measurement network, it is not initially oriented, although measurements can immediately be made. Since polar measurements represent 3D values, it is possible to display these in the instrument coordinate system.

These instrument coordinate values apply only to the instrument where the measurements are made. Since the corresponding station is not oriented, these values cannot be related to any other part of the measurement network. and other points measured from a different station cannot be viewed in this coordinate system

Interferometer

An optical instrument that measures a change of distance using a property of waves known as **interference**.

The movements of waves are additive. Although the effect is general, it is easiest to visualize the effect with two sinusoidal wave sources of the same frequency and amplitude.

If waves from the sources meet at their peaks, their effects add together to create a peak of twice the size. If the crest of one meets the trough of the other then they cancel out. Somewhere in between gives an intermediate result.

An interferometer uses very pure laser light. For practical purposes this light can be taken as a sinusoidal wave of a single frequency and constant amplitude whose wavelength is very accurately known.

The laser beam is transmitted to a retro-reflector and the return beam is combined with the transmitted beam. If the distance to the reflector and back is an exact number of wavelengths the beams add and produce a bright signal. If the distance is an exact number of half wavelengths the beams cancel out and the result is a dark spot. If the reflector is slowly moved, bright and dark **fringes** can be observed at the interferometer. By counting the fringes a change of distance can be calculated.

Intersection

Diagram: Intersection of target
Diagram: Intersection of plane and sphere
1) Relating to pointings at targets
Intersection is the creation of 3D point coordinates from two or more theodolite or camera pointings. Theodolite and camera stations must be *oriented*. Each pointing from a theodolite or camera station indicates the direction of a target point but not its absolute position. A second pointing is required from a different station to fully locate the target point in 3D space. Multiple pointings can improve the accuracy of the 3D location.

The pointings do not normally intersect exactly at a point in 3D space and some form of *least squares* analysis is required to calculate the target coordinates which are a best fit to the pointings. The diagram indicates this practical effect.

2) Relating to shapes
An intersection of shapes is the new shape element which results at the points of intersection. The diagram shows the intersection of a plane and sphere. The result is a circle.

Diagram: Intersection of target

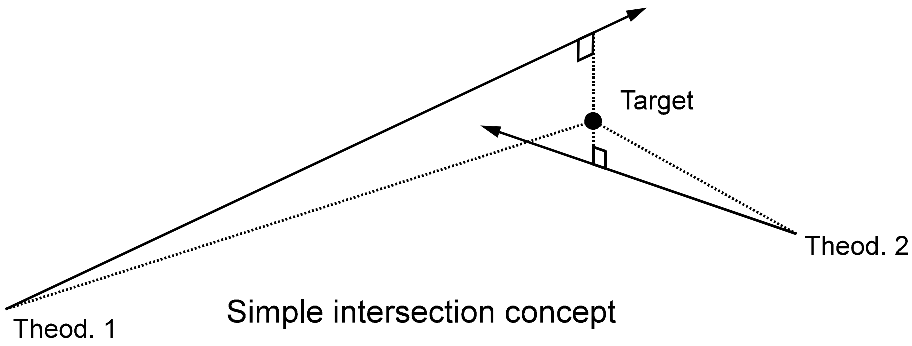
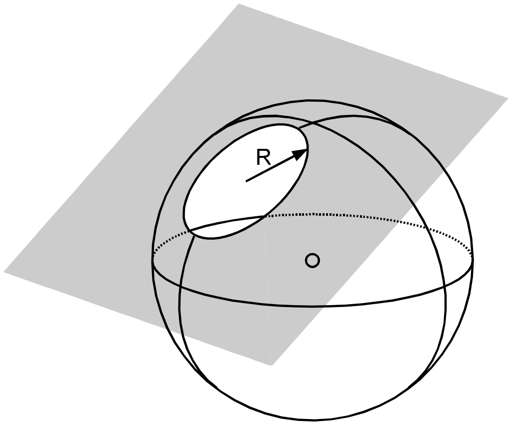


Diagram: Intersection of plane and sphere



IR

Short for infrared *light*.

Isometric view

Example: Isometric view of cube

A graphical view or projection in which all 3 axes of the *coordinate system.* indicate the same scale.

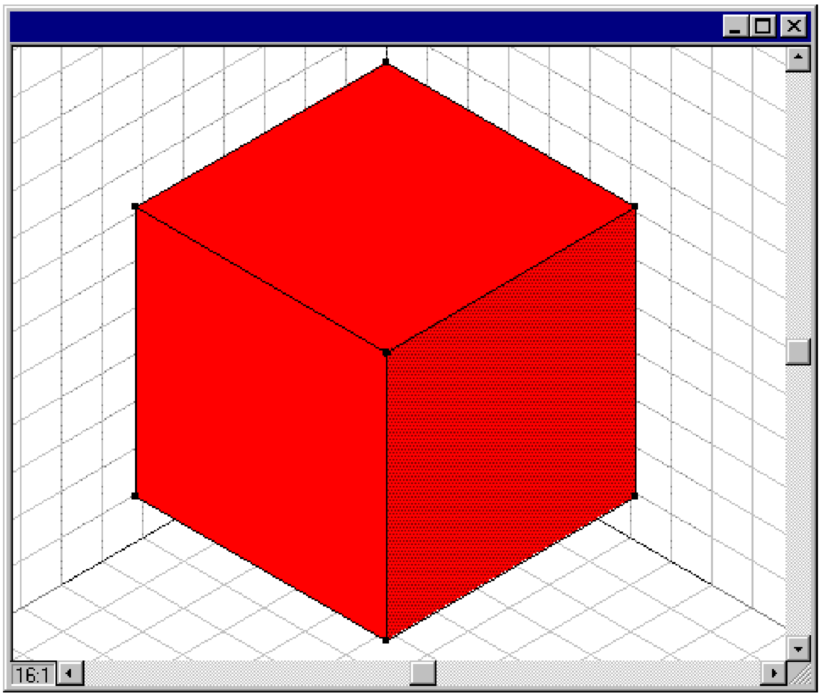
The projected axes make an angle of 60° with their neighbours.

An isometric view gives a 3-dimensional appearance to an object but this is not the type of view which is recorded by the human eye. See *perspective view*.

Alternatives:

Isometric projection

Example: Isometric view of cube



View - Isometric.bmp

Iteration

In mathematics, repeating a process of comparison and modification until some value has been optimized is called iterating towards a solution and each of the steps is a single iteration. The process itself may be called an **iterative process**.

The term is related to the normal English word "reiterate" meaning "to repeat/do again".

Iteration is needed when it is not possible to compute an optimized answer in a single step. This is because many mathematical formulations are **non-linear**, i.e. the parameters to be calculated appear in squared, cubic and higher powers or are multiplied together. With a few exceptions, a one-step solution does not then exist.

Before iteration is possible, some other estimation method must generate approximate values for the required parameters. These have several names:

- **Approximate values**
- **Starting values**
- **Initial values**
- **Trial values**

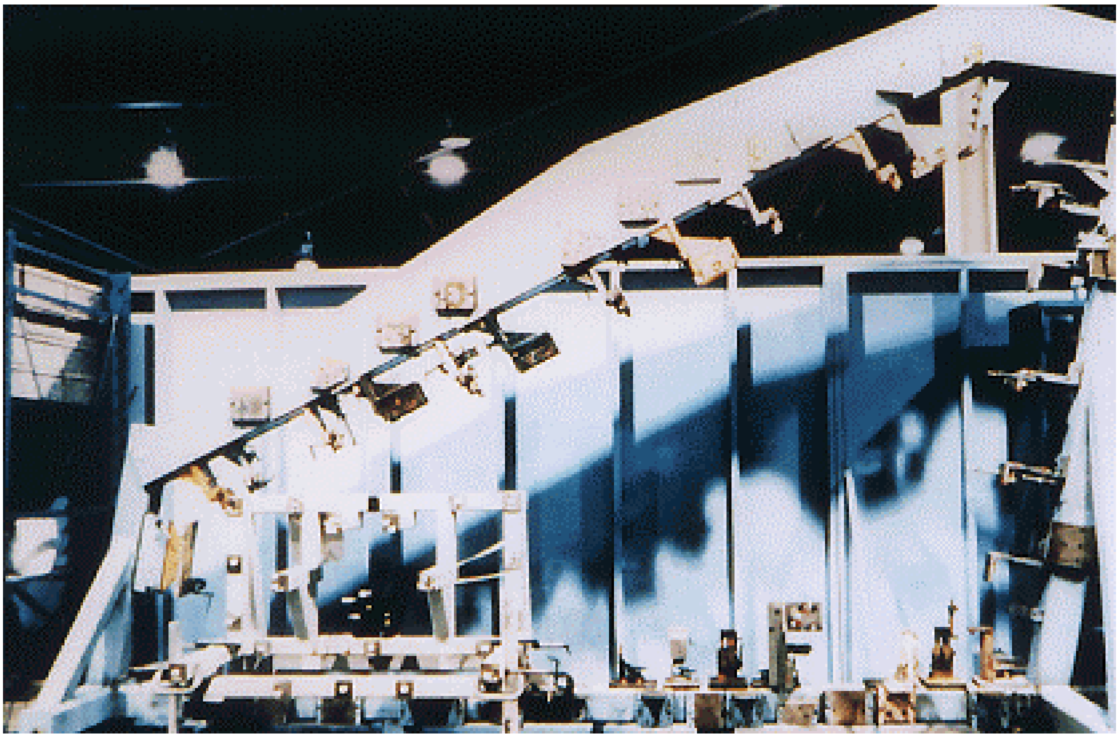
J

Jig

Photo: Tooling jig
A mechanical device designed to hold and locate a component during machining and to guide the cutting or drilling tool.

Alternatives:
Tooling jig
Fixture
Tooling fixture

Photo: Tooling jig



Job

Every measuring task which generates a related set of 3D data describing one or more *objects* is known to ***Axyz*** as a job.

The data relating to a job are stored in the *job file*.

Job file

The file in which all information relating to a particular measurement *job* is stored. This file is a *database.* containing different types of data such as measurements, calculated coordinates and administrative information.

When a new job file is created a copy is made of a **master job file** or **master database** which function as templates. A default master is supplied as part of the ***Axyz*** installation but the user may modify this or define others as the master.

Jointed arm CMM

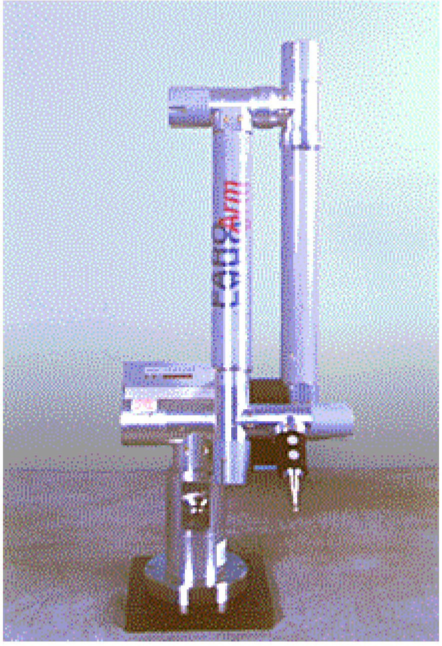
Photo: FARO arm
This device looks like a robot arm but it is not powered and is moved only by hand.

It consists of accurately machined fixed links and joints with accurate angle encoders. It has a touch probe whose 3D location can be calculated from the open polygon defined by the lengths of the links and the current encoder angles of the joints.

These machines are lightweight and easily moved around a workspace. It may therefore also be called a **portable CMM** . (See also Coordinate Measuring Machine.)

The photo shows such a device manufactured by **FARO** Technologies, Inc.

Photo: FARO arm



K

Kern

Kern was a Swiss manufacturer of optical equipment for map making and industrial measurement. Founded in 1819 by Jakob Kern it has been part of Leica since 1990.

Kern instruments are no longer manufactured but the Kern E2 theodolite is still in use for industrial measurement.

L

LAN

Short for *Local Area Network.*

Laser

Short for Light Amplification by Stimulated Emission of Radiation.

Gases such as argon and a helium/neon mixture can be energized and made to emit very pure *light* of a single frequency (colour). The fact that the light is pure and can be confined to a narrow beam over long distances makes it very suitable for metrology purposes.

It is also possible to generate laser light from a solid state *diode*. This **diode laser** has the advantage of being very small and can easily be incorporated into optical devices such as a *laser eyepiece*.

Least squares

A general mathematical technique used to calculate optimal values of parameters such as point coordinates derived from theodolite pointings.

Since measurement accuracy is limited by physical tolerances and random effects, and more measurements are normally taken than are strictly needed, any set of measurements is actually inconsistent. For example, a circle fits exactly to 3 points. If more than 3 points are measured in order to calculate the radius of a particular circle, then different sub-groups of 3 selected from the measurement set will generate slightly different values of the radius.

Least squares methods find single solutions for the derived values which represent best fits to the inconsistent measurement data. The **best fit** operates by creating a mathematical model of the situation and calculating differences between modelled values, such as modelled measurements, and actual values. The parameters of the model, such as the radius of a circle, are altered step by step in a sequence of *iterations* until a best fit between modelled measurements and actual measurements is obtained. The best fit is determined by examining the sum of the squares of the differences. When this is a minimum, the model and its parameters are assumed to be the best description of the actual measurement situation.

Least squares is normally applied when there is more data than mathematically required to solve the problem and this data is not **consistent**. This is an **overdetermined** situation in contrast to an **underdetermined** situation in which there is insufficient data to calculate the required parameters. As described above, measured data is treated equally but a further level of sophistication is possible by using *weights* to allow for data of varying quality and type. Yet more refinement is possible with the concept of **constraints**. These imply some additional restriction on the solution, for example the restriction that all theodolite stations are levelled. Such restrictions are ultimately also another measurement to be evaluated but are often not directly measured and can often be removed without causing the solution to fail. A **constrained** solution applies constraints. In an **unconstrained** solution they are removed or else do not exist. Constraints may improve the stability and accuracy of a solution.

LED

Short for Light Emitting *Diode*

Leica

Leica was originally the name of the camera manufactured by Ernst Leitz in Germany. The name derives from **Lei**tz **Ca**mera.

In the early 1990s a number of companies amalgamated under the name "Leica". These included *Kern*, *Wild*, Leitz and Cambridge Instruments. Since then a number of re-organizations have taken place.

Currently (1999) Leica is divided into 3 groups. Leica Geosystems (home of Leica's industrial measurement), Leica Microsystems and Leica Camera. In time each group is expected to become an independent company.

Lens

Diagram: Convex prism lens
Diagram: Concave prism lens
A piece of transparent material, typically glass, used to converge or diverge transmitted *light* and so form optical images of objects.

A simple lens typically has two ground spherical surfaces and operates by *refracting* incident light. An even simpler concept is a crude lens built up of prisms. The diagrams show a simplified situation in which parallel rays are refracted by a set of prisms to an image point. These prisms can be regarded as sections of a simple lens. Note how a convex lens focuses light to a real image point and a concave lens diverges light from a virtual image point.

In simple and approximate terms, the **lens axis** is the line of symmetry through the lens and the **focal length** is the distance from the centre to the point where parallel object rays are focused.

Refraction by a prism causes white light to be dispersed into its constituent colours and the same effect is therefore present in a simple lens. This chromatic *aberration* is just one of many negative effects which detract from the design function of a lens which is to generate good optical images. Fortunately simple lenses can be combined to reduce these effects. A combination of two lenses or **doublet** can greatly reduce chromatic aberration. More complex **compound lenses** can significantly reduce many aberrations and distortions, although for metrology purposes residual *lens distortion* must still be taken into account in order to obtain the highest measurement accuracy.

Diagram: Convex prism lens

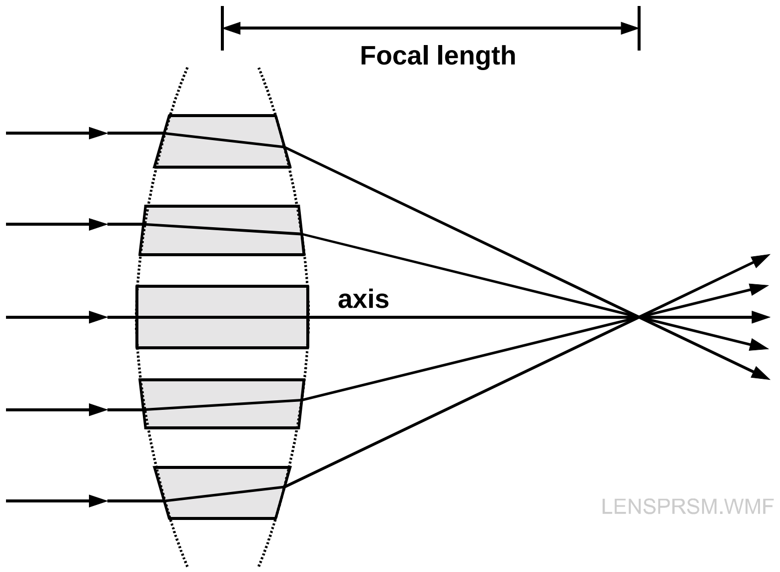
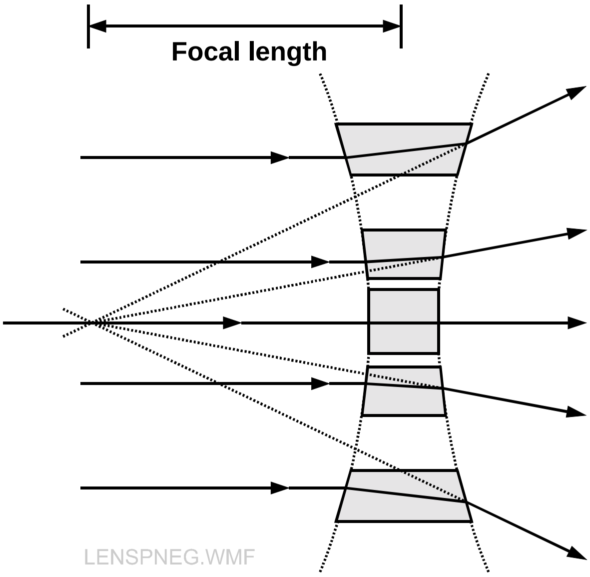


Diagram: Concave prism lens



Lens distortion

Diagram: Lens distortion

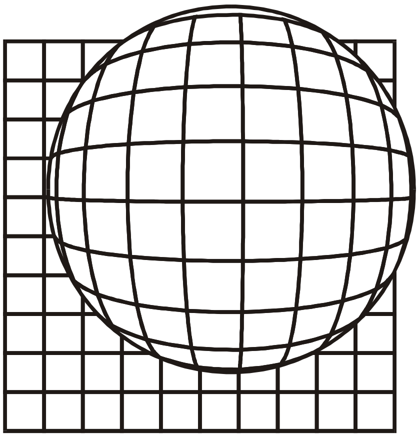
Glass lenses do not produce perfect images of objects. For measurement purposes a glass lens should ideally create images like a *pinhole camera*. In particular, straight lines should image to straight lines.

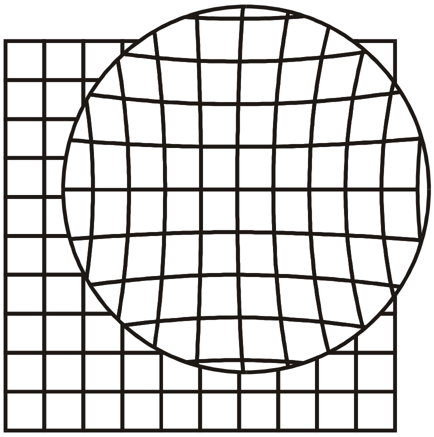
In real lenses the images of straight lines are curved, creating **barrel distortion** and **pincushion distortion**.

Lenses have other imperfections and distortion is only one of a general class of optical *aberrations*.

Alternatives:
distortion
geometric distortion

Diagram: Lens distortion





Barrel distortion **Pincushion distortion**

DISTORT.WMF

Light

Light is one form of **electro-magnetic radiation**. This has properties which can sometimes be analysed as a stream of particles and sometimes as a wave motion. Wave motion is particularly important in the design of optical instruments. For example, the operational principle of an *interferometer* relies on the properties of waves.

The wave motion has two components which are oscillating electric and magnetic waves. The frequency of the motion is interpreted by the human eye as colour and white light, which is a mixture of frequencies, can be made to display the familiar spectrum of colours from red (long wavelength, low frequency) to blue (short wavelength, high frequency).

In large-scale metrology considerable use is made of visible light, but instrumentation also makes use of non-visible light such as **ultraviolet** (at the blue end of the spectrum) and **infrared** (at the red end of the spectrum), as well as radio waves.

Light of a single frequency or colour is known as **monochromatic** . A *laser* is one device which can produce light which is, for practical purposes, monochromatic.

In free space a small (point) source of light will radiate its energy equally in all directions. As it travels through space a pulse of light emitted from this source can be visualized as an ever expanding sphere. This gives two convenient concepts. A **ray** of light is a small part of the sphere travelling in a straight line on a radius centred on the source. The **wavefront** is the surface of the sphere, always perpendicular to the corresponding rays. Wavefronts can be distorted by optical systems. For example, *cameras* will change the curvature of an expanding wavefront from an object point so that the rays captured by its lens are focused back to a sharp image point. Some systems are designed to produce parallel bundles of rays with associated plane wavefronts. A laser produces light almost meeting this condition, so that the very narrow beam it emits travels a long way with little change in diameter.

Local Area Network (LAN)

A communications system which connects a group of computers, or microprocessor controlled devices, by hard wired or radio links and defined software **protocols** which regulate how data is transmitted between them.

A LAN is used by the ***Axyz*** system to link together multiple trackers and to enable the individual subsystems of a tracker to communicate.

In order to connect physically to a LAN, each device needs a PC card known as a **LAN adapter**. A PC may have more than one LAN adapter. For example, it may control a tracker system and also be connected to an office e-mail network. Individual adapters are recognized by individual LAN adapter numbers or **LANA numbers**. .

To ensure correct data exchange, each device connected to a LAN must have a unique address. The ***Axyz*** system uses integer numbers, known as **LAN ports,** as addresses. This name indicates an equivalence with the *COM ports* used for connecting other equipment such as theodolites.

Local coordinate system

Within ***Axyz*** this term is used to indicate a coordinate system most relevant to the feature which defines its origin, i.e. the coordinates and axes are primarily of local interest rather than relevant to other measured features.

Example 1: Local shape coordinate system
When a circle is created its centre defines the origin of a local coordinate system. The xy axes of this system are in the plane of the circle and the z axis is perpendicular to the plane.

Example 2: Local station coordinates
The first theodolite station processed in a measurement *network* may define a local coordinate system with origin at the centre of rotation and instrument axes used as coordinate axes.

Note
Within ***Axyz*** a local coordinate system is applicable throughout the measurement space, i.e. you can transform between local coordinate systems. Other technical fields distinguish between unconnected "local" coordinate systems and a generally applicable **global coordinate system**. For comparison, see also *instrument coordinates*.

Local coordinates

Coordinates measured in a *local coordinate system.*

LTM

Short for **Laser Tracker Module**, one of the ***Axyz*** software modules.

M

ManCAT

Short for Manual Computer Aided Theodolite system.

This was one of Leica's earlier 3D coordinate systems based on theodolites. It was manufactured by *Wild* Heerbrugg.

Master gauge

This is a reference object used in constructing and inspecting tooling *jigs* used in large scale manufacturing, for example aircraft and automobile manufacture.

The master gauge provides accurately located points and surfaces in accordance with the CAD design for the object under construction. It is a robust construction maintained under careful conditions.

Matrix

Diagonal matrix
Unit matrix
Transpose of matrix
Symmetric matrix
Inverse of matrix

A rectangular array of numbers which can be handled as a single entity.

Matrix analysis simplifies the handling and solution of sets of equations which frequently arise in the analytical procedures of large scale metrology. For example, see *rotation matrix*.

A simple set of equations might look like this:

$$5x_1 + 2x_2 + 1x_3 = 20$$
$$2x_1 + 4x_2 + 2x_3 = 16$$
$$1x_1 + 2x_2 + 3x_3 = 10$$

The x's are the unknown parameters which must be calculated to fit the equations. In matrix format this would be written:

$$\begin{bmatrix} 5 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 20 \\ 16 \\ 10 \end{bmatrix}$$

Which is then written more concisely in matrix notation as:

$$Ax = K$$

$$\text{where} \quad A = \begin{bmatrix} 5 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 3 \end{bmatrix} \quad \text{and} \quad K = \begin{bmatrix} 20 \\ 16 \\ 10 \end{bmatrix}$$

Matrices may be square, with equal numbers of rows and columns, or rectangular, with unequal numbers.

See the detail boxes for examples of special matrices and procedures:
Diagonal matrix
Unit matrix
Transpose of matrix
Symmetric matrix
Inverse of matrix

Diagonal matrix

$$\begin{bmatrix} 5 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

A diagonal matrix has zero values on the off diagonal elements.

Unit matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

A unit matrix is a diagonal matrix with unit values on the diagonal. When applied to a set of parameters it imposes no change. It has the same effect as the value "1" in normal algebra, e.g. 1 x = x.

It is normally written as the letter "I", i.e. I x = x

Transpose of matrix

$$A = \begin{bmatrix} 5 & 8 & 7 \\ 2 & 4 & 1 \\ 6 & 0 & 3 \end{bmatrix} \text{ and } A^T = \begin{bmatrix} 5 & 2 & 6 \\ 8 & 4 & 0 \\ 7 & 1 & 3 \end{bmatrix}$$

In a transposed matrix the rows become columns and vice versa, e.g. row 3 becomes column 3. The transpose of a matrix A is written as A^T.

Symmetric matrix

$$A = \begin{bmatrix} 5 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 3 \end{bmatrix} \text{ and } A^T = \begin{bmatrix} 5 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 3 \end{bmatrix}$$

A symmetric matrix has off diagonal elements such that it is equal to its own transpose, i.e. row 1 of A is the same as column 1 of A^T, etc.

Inverse of matrix

In normal algebra the expression:

$$ax = k$$

can be solved for x by dividing by a, i.e.

$$x = \frac{k}{a}$$

The matrix equation:

$$Ax = K$$

cannot be solved in the same way as division by the matrix A does not exist. Instead the inverse of a matrix can be calculated. For a matrix A the inverse is written A^{-1}. When the inverse multiplies the original matrix the result is a unit matrix, I.

To solve the matrix equation, both sides are multiplied by the inverse:

$$A^{-1}Ax = A^{-1}K$$

but

$$A^{-1}A = \text{unit matrix } I\text{, therefore}$$

$$Ix = A^{-1}K$$

But the unit matrix has no effect on x, therefore:

$$x = A^{-1}K$$

Note
It is not always possible to calculate an inverse.

Mean error

Another term for *variance factor*.

This term was used in Leica's *ManCAT* system as a more user-friendly term for non-mathematicians. Unfortunately there is a potential confusion of terminology. For example, variance factor itself has 4 different names and German textbooks use a statistical figure called the "mittlerer Fehler" which translates as "mean error" and is the square root of the variance factor.

For this reason ***Axyz*** makes use of an existing recognized term, i.e. variance factor.

Note
Do not confuse this term with **mean value**.

Measured control point

Once measured, control points are subject to measurement tolerances and their calculated locations will not, in general, exactly match the design values. This point type indicates that the coordinate values are measured, not design values.

See *point* for a complete summary of point types used in ***Axyz***.

Measured point

A target point which is directly located by theodolite intersection or polar measurement. This is the most common point type in use by ***Axyz***.

Measured objects are mainly represented by collections of measured points.

See *point* for a complete summary of point types used in ***Axyz***.

Measurement

Values taken from the encoders of an instrument and corrected for instrument calibration only.

Many measurements in large scale metrology are made by sighting through optical instruments. Visual sighting is also known as **observation** and this is often an alternative term for "measurement".

It is also common to refer to measurements as *raw data*.

Metrology

The science of weights and measures. For ***Axyz*** users this mostly tends to mean the science of dimensional measurement in one, two and three dimensions.

Since ***Axyz*** users have applications where typical dimensions are in the range 1m - 50m, the science in this case may be further qualified by the description **large scale metrology**.

The use of optical instruments and measurement techniques is a key feature of large scale metrology.

MTM

Short for **Multiple Theodolite Module**, one of the ***Axyz*** software modules.

N

Near point

The measured target on a *hidden point rod* which is closest to the tip (the actual hidden point).

Network

In an ***Axyz*** measurement job, the measurement network is the arrangement of oriented instrument stations and scale bars which surround the object(s) being measured and from which the final 3D coordinates are generated.

Several instrument *setups* may be required in order to create a full measurement network.

Alternatives:
Measurement network

NIVEL

Photo: NIVEL 20
Diagram: Operation of dual-axis tilt sensor
NIVEL comes from the German word "Nivellierinstrument" meaning a surveyor's level.

The NIVEL is a dual-axis **tilt sensor** which can automatically detect deviations from the vertical in two directions. It is a stand-alone sensor which can be used for general monitoring purposes or to reference other instruments, such as the laser tracker, to the vertical.

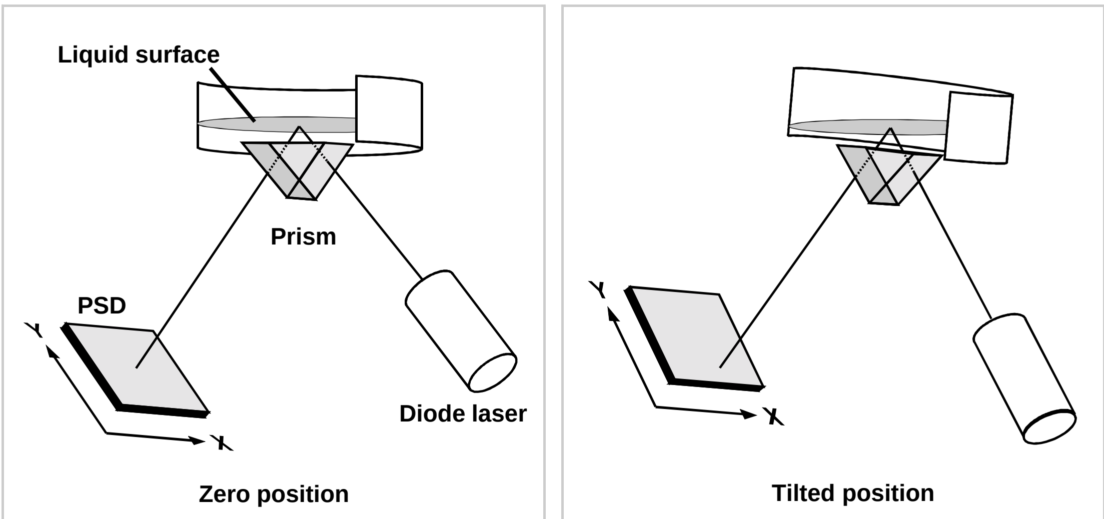
It operates by projecting a laser beam from a diode *laser* onto the under surface of a liquid. This surface acts like a mirror which is always level and reflects the beam onto a position sensing device (*PSD*). If the device is tilted the spot position changes on both the PSD axes, thus providing a signal which can be converted into a measure of tilt.

The NIVEL can sense tilts within approximately ±5 arc minutes of the vertical and to sub arc second accuracy.

The tilt sensors incorporated in Leica theodolites and Total Stations use the same principle of operation. However here the sensor signal is designed to be set to zero by adjusting the instrument's footscrews so that the *standing axis* is exactly vertical.

Photo: NIVEL 20

Diagram: Operation of dual-axis tilt sensor



Normal distribution

Diagram: Normal distribution
Diagram: Probability density
Concept: Probability density

When a measurement is repeated many times, *random errors* cause small differences in the measured values. These values fit a common pattern called the normal distribution which shows how they are distributed around the true value. Most measured values are close to the true value, with only small numbers of measurements which are too high or too low.

The diagram shows 200 measurements of a distance whose average value is 810.17 units. Instead of showing the actual number of measurements which generate a particular value, their relative proportion is shown as a rectangle. For example, 20 measurements have the value 810.15. These represent 10% of the measurements or a relative number of 0.1. This value approximately indicates the **probability** that a particular measurement will occur.

The superimposed bell-shaped curve is the mathematically defined normal distribution curve and is used for error analysis. It is, in fact, a curve of **probability density**. See the concept box for more information.

Alternatives:
Gaussian distribution (named after the German mathematician Karl Friedrich Gauss)

Diagram: Normal distribution

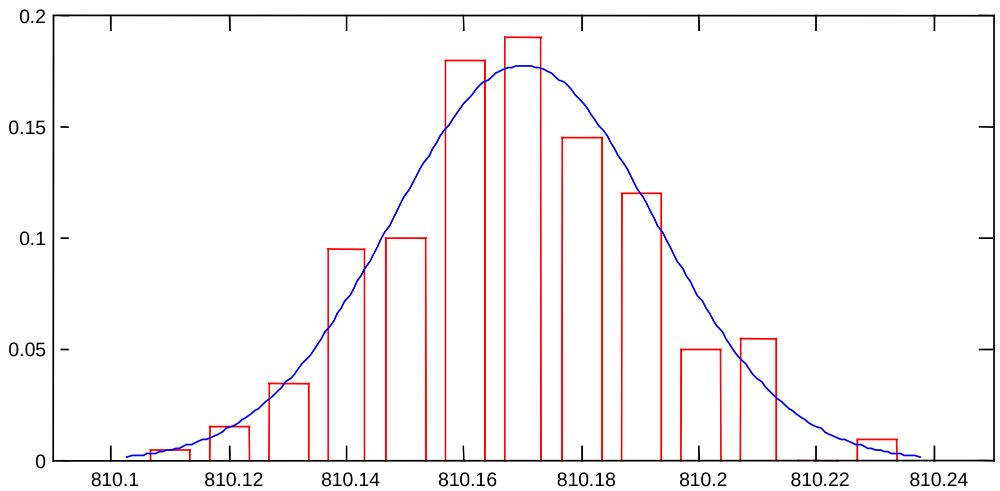
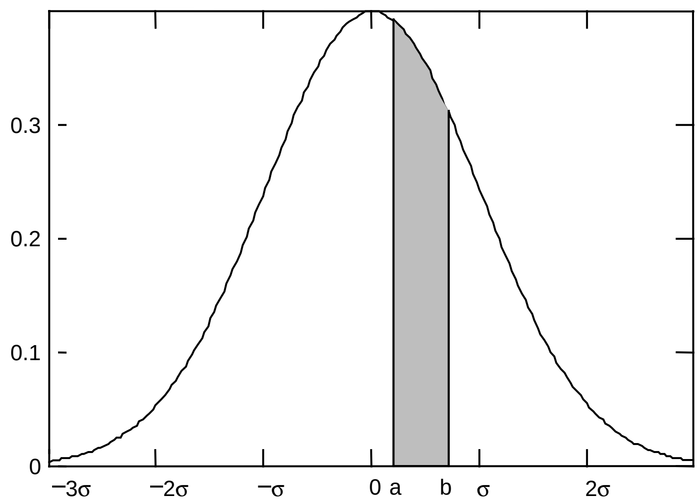


Diagram: Probability density



Concept: Probability density

The normal distribution curve represents probability density, i.e. a probability per unit. It can be used by asking: "What is the probability that a measurement lies between value a and value b?" The shaded area under the curve then indicates the probability (diagram). You do not use the curve to ask: "What is the probability that a measurement has value c".

Consider an analogy. You have a bar made of some composite material whose density varies in the same bell-shaped way. In casual conversation you can say: "The bar is heavier in the middle than at the ends" and the fact that the density of the material is highest in the middle clearly indicates this. However to be quite specific you would have to say that the weight of a section cut from the middle is heavier than the weight of a similar length section cut from the end. To obtain a section you must cut it out between positions a and b but it is meaningless to refer to the weight of a cross section at position c.

O

Object

In ***Axyz*** an object is a physical item, such as a wing panel or car body, for which 3D coordinates are required.

In the *job file* objects are defined by sets of measured points, shapes and coordinate systems which are grouped together into different *workpieces.*

Object coordinate system

The most meaningful coordinates which describe an object are generally defined by selected features on the object itself. By suitably locating the origin and axes of the coordinate system, measured coordinate values can correspond very closely to the design coordinates used to manufacture the object. This is known as an object coordinate system and is very convenient for building and inspecting features.

Object coordinates

Coordinates measured in an *object coordinate system.*

Optical tooling

The application of optical methods, based on the use of telescopes, prisms and mirrors, to define parallel and orthogonal lines and planes for purposes of mechanical *alignment* and assembly.

Alternatives:
Optical alignment (British usage)

Orientation

3D coordinates cannot be generated until all the stations involved in measuring all or part of an object are linked together into a common measuring *network* in which their positions and tilts are known. This procedure is known as orientation and it generates 6 **orientation parameters** for each station, i.e. 3 coordinates of position and 3 *rotation parameters*. These also correspond to the 6 mechanical *degrees of freedom* necessary to define any object's location and angular orientation.

The process of orientation is **non-linear** and is carried out in two phases. The first phase involves the use of particular *orientation methods* which generate approximate positions and tilts for the stations.
The second phase, also called a *bundle adjustment* optimizes the results of the first phase.

If an ***Axyz*** network is composed of only a single measuring station, then this station is automatically recognized as oriented in a coordinate system defined by the axes of the instrument which occupies the station.

Orientation methods

A particular tailored measurement scheme from which can be found the position of one measuring station with respect to another, or to an existing coordinate system.

The particular features of an orientation method are:

- Limited numbers of measurements
- Direct or straightforward calculation of relative position and tilt

Optimized procedures are often not used and so the results must be further optimized by more complex, **non-linear** methods.

Example orientation method 1
Levelled theodolites can make use of *collimation* between the instruments, with an estimation of separation.

Example orientation method 2
Polar measuring systems can utilize a *3D transformation* by measuring at least 3 points in common with an existing station or already known in an existing coordinate system.

Orientation to control

Orientation to control makes use of control points which force the results into the coordinate system of the control and influences (controls) the shape of the measurement network.

It may be called an object orientation since the control coordinate system generally has some direct meaning to the object. For example it represents the coordinate system used in the design and manufacture of the object.

Alternatives:
Controlled orientation
Object orientation

Orthogonal

Perpendicular, involving right angles.

Geometric features such as lines and planes are orthogonal if they intersect at right angles. 3 such features, each of which is orthogonal to the other two, are usually described as **mutually orthogonal**.

Orthographic projection

A graphical representation of an object in which the object is projected along lines perpendicular to the projection plane.

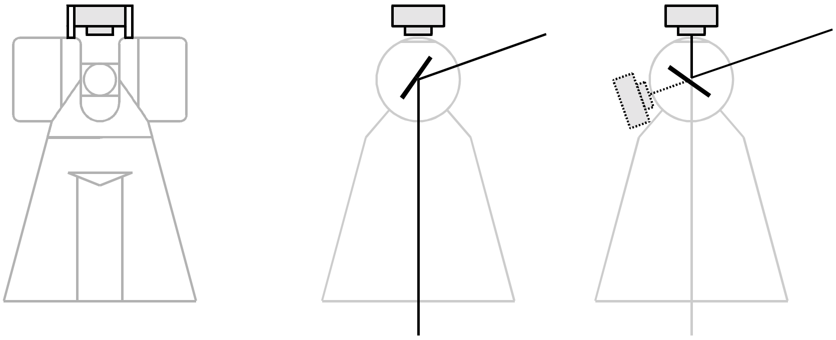
This form of projection is typically used to give plan and elevation views of objects to be constructed, such as buildings or machinery. In the projection the object is represented at some scaled version of its actual size.

Overview camera

Diagram: Overview camera
Photo: Overview camera
The overview camera is an accessory for the *laser tracker*. It is mounted on the head. The mirror in the head is normally used to reflect the laser beam out onto the target. However the mirror can be rotated to enable the overview camera to provide a view down the laser beam axis towards the target area.

The device has its own illumination and is useful for manually locating reflectors are re-setting the beam on them.

Diagram: Overview camera



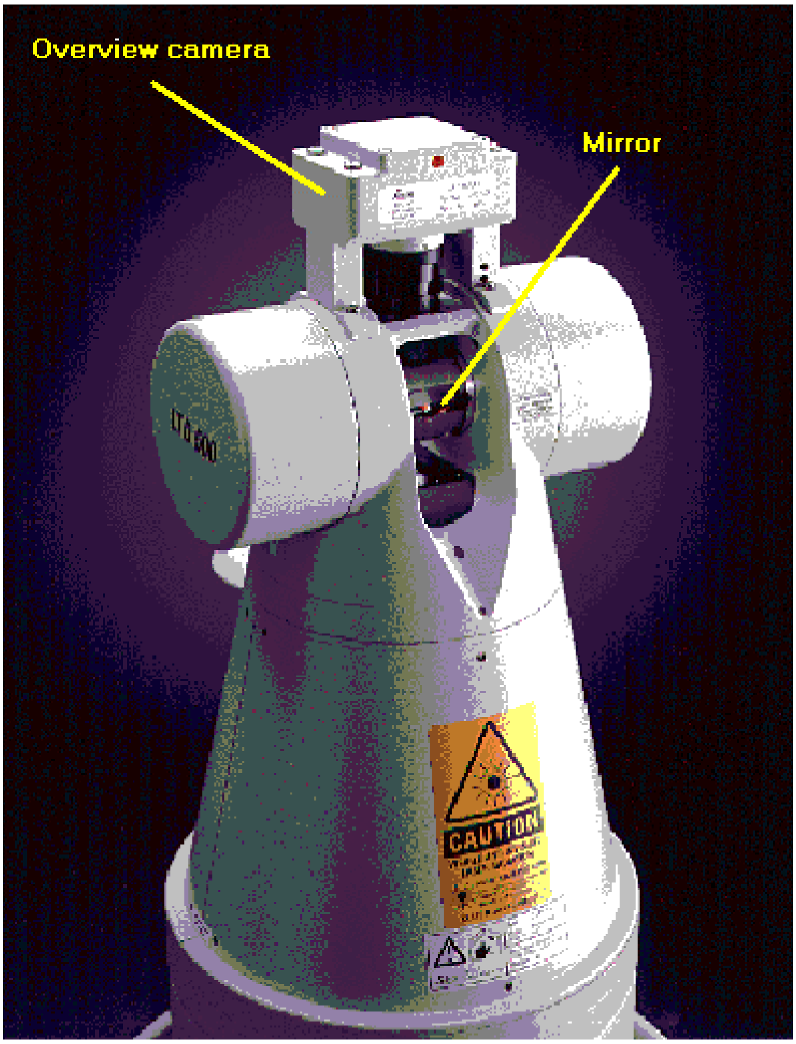
Camera mounted over mirror

Mirror position 1 reflects laser beam to target

Mirror position 2 reflects camera axis towards target

OVRVWCAM.WMF

Photo: Overview camera



P

Phase

Diagram 1: Phase shift
Diagram 2: Out of phase
Diagram 3: In phase

Light and radio signals are a form of wave motion which is described by sinusoidal waves. The phase of the motion is the position along the wave.

Phase is particularly relevant in metrology for purposes of distance measurement. Here the **phase angle** between two waves is important. The two waves are normally a transmitted wave and its own reflection back from a retro-reflector. Both waves are compared at the transmitting instrument.

The diagrams show waves of the same wavelength, oscillating at 0.5 cycles per second over a period of 5 seconds.

Diagram 1 shows one wave (dashed line) which is shifted by a phase angle equivalent to ¼ wavelength with respect to another wave (solid line).

Diagram 2 shows the waves with a phase shift of ½ wavelength. Here the peaks of one wave coincide with the troughs of the other.

Diagram 3 shows the waves with a phase shift of 1 wavelength, which is the same effect as zero phase shift.

Diagram: Phase shift

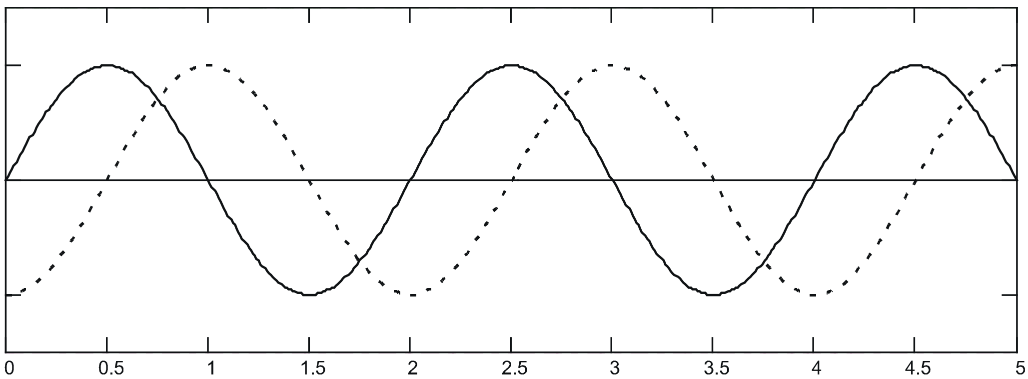


Diagram: Out of phase

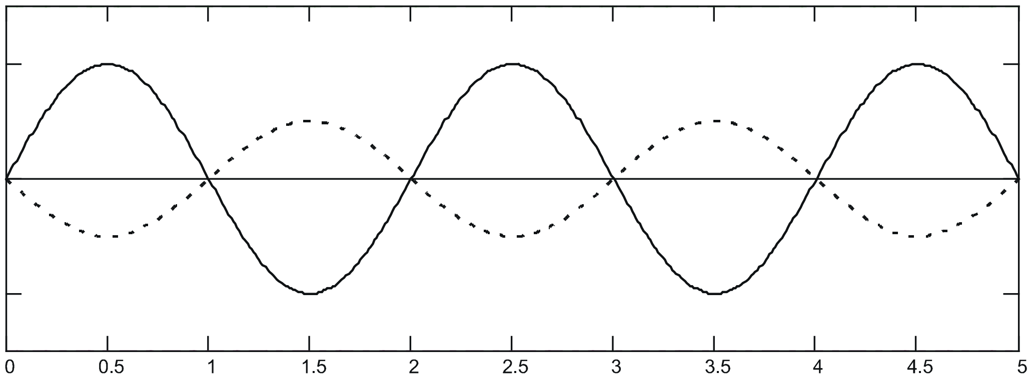
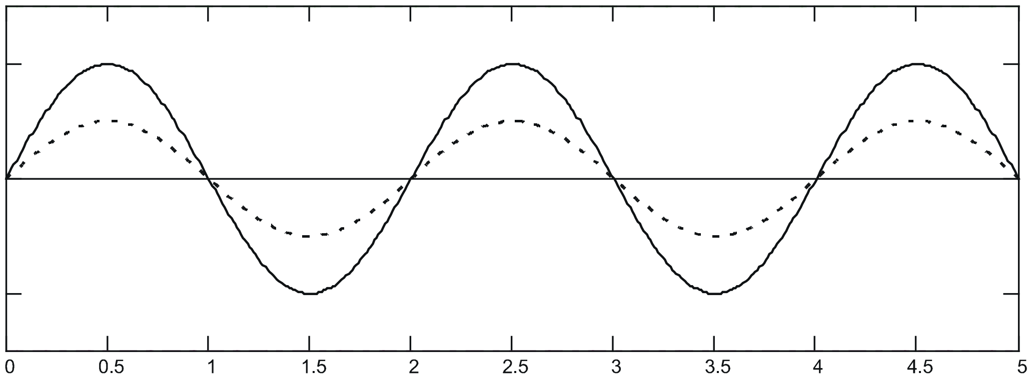


Diagram: In phase



Photogrammetry

The science of making accurate 3-dimensional measurements from photographs and photographic *images*.

The term "photogrammetry" is normally associated with conventional photographic imaging based on film and requiring chemical processing to produce measurable images.

If modern technology is used, based on fully electronic recording of still images and digital image processing, then the science is often called **videogrammetry**, to underline the use of a video image and related techniques.

The fundamental 3D measurement technique in photogrammetry is *triangulation*. Each identifiable target point in an image provides a direction in space, from the projection centre of the *camera* through the equivalent position on a positive image. This is a reverse projection of the rays which originally formed the image point. When at least two directions to the same 3D point are established, one from each of two camera locations, then the target location can be determined.

Pinhole camera

Diagram: Image creation by pinhole camera
Diagram: Spatial projection by back projection
Diagram: Local camera coordinate system and parameters
The pinhole camera is a light-tight box with a small hole in one face. This allows a very narrow bundle of rays from an object point to pass through into the box and create a small image spot on the opposite face.

A pinhole of the right size will ensure that the image spots from all object points will together create a reasonably bright, reasonably sharp complete image of the object.

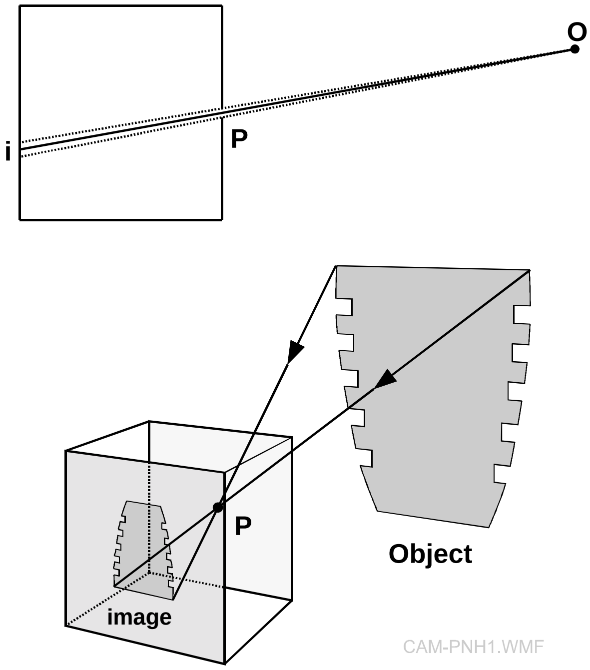
The imaging geometry is characterized by the central ray of the bundle which is a straight line from the object point through the centre of the pinhole, also called the **projection centre**, to the centre of the image spot. This well defined geometry ensures that images are free of distortion. For example, straight lines in the object space will image as straight lines in the image.

The pinhole camera provides a simple geometric reference concept with which to compare real *cameras*. Spatial directions to object target points are created by projecting the image back through the pinhole. The pinhole provides the origin of a local right handed coordinate system with x,y parallel to the image plane. It is convenient to use this system in conjunction with a positive image to define a target's direction as a local vector.

The **camera axis** is the perpendicular from the pinhole to the image plane and intersects it in the **principal point** P. The separation of image plane and pinhole is the **principal distance** or **camera constant** c. The image vector is (x,y,z) where x,y are the **image coordinates** and z is the principal distance. The z value is always negative because of the positive direction of the z axis.

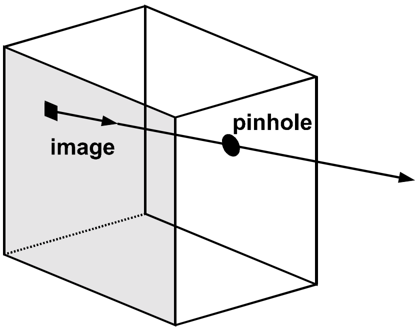
The location of the principal point in the image, and the principal distance, are measured values which are subject to uncertainty and are often calculated as part of the *camera calibration.*

Diagram: Image creation by pinhole camera



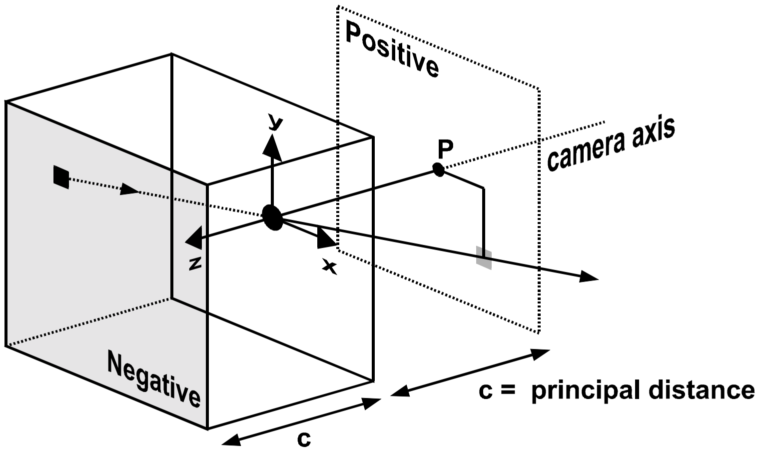
CAM-PNH1.WMF

Diagram: Spatial direction by back projection



CAM-PNH2.WMF

Diagram: Local camera coordinate system and parameters



CAM-PNH3.WMF

Point

Table of object points
Table of other points
All objects measured by ***Axyz*** are effectively digitized and represented by the resulting collection of 3D points. Each point represents a single 3D location. Most point data managed by ***Axyz*** relate to the measured object and may be collectively called **object points.** Other point data exist which relate to the measurement network or object design.

The tables show the full range of point types defined for use by ***Axyz***.

Alternatives:
Point of interest

Table of object points

Point type	Remarks
Measured	A target point which is directly located by theodolite intersection or polar measurement.
Entered	A point input manually or imported from a file. It provides a general purpose facility for checks and calculations.
Control	Control points have design coordinates which are used exclusively to modify or "control" the effects of an orientation procedure during the phase of bundle adjustment.

Measured Control	Once measured, control points are subject to measurement tolerances and their calculated locations will not, in general, exactly match the design values. This point type indicates that the coordinate values are measured, not design values.
Calculated	A point derived by calculation, such as the intersection of two lines. A derived point such as the local origin of a calculated shape may also be stored as a calculated point.
Hidden	The point, often the tip, on a hidden point device, which is calculated by measurements to the device (offset) points.
Device	The current locations of the offset targets on a hidden point device.

Table of other points

Point type	**Remarks**
Reference	Reference points represent design locations and are used for purposes such as: • 3D transformations • Comparison with measured object points • Build and Inspect routines
Scale	Scale points are the measured locations of targets on *scale bars*.
Orientation	Orientation points are locations measured only to improve the calculation of an *orientation*. ***Axyz*** does not define a separate point type for this purpose.

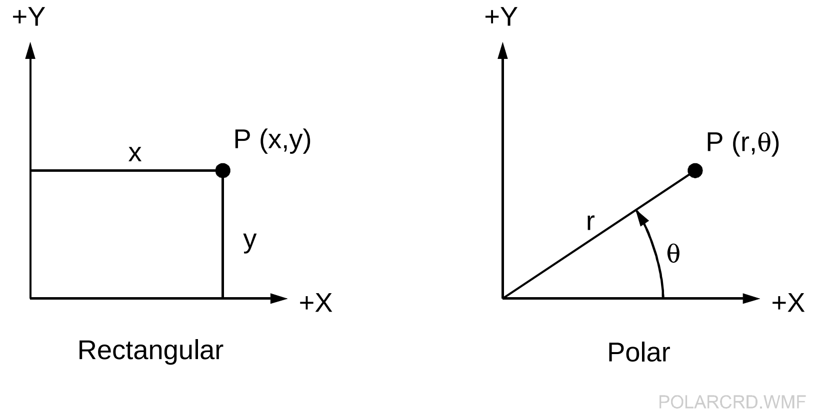
Polar measurement

Diagram: Polar coordinates
A technique by which a target is located in 3D space by measuring its distance and direction from a fixed, known location.

The method involves a distance and two angles. More correctly this is a location by *spherical coordinates* which are a triplet of 1 distance and two angles. Strictly speaking **polar coordinates** only apply in two dimensions where points are located by distance from the origin and angle from the X axis.

This type of measurement can be provided by Total Stations and laser trackers.

Diagram: Polar coordinates



Polarization

Light waves are **transverse waves**, i.e. they oscillate perpendicular to the direction in which they travel. Normally the electric component of the waves oscillates in all directions. Polarization restricts the vibration to a particular **plane of polarization** by passing the light through a material such as **Polaroid**.

Once polarized, further transmission through a polarizing material will reduce the amount of light transmitted. Only if both planes of polarization line up will all the light energy be passed through. If the planes are at right angles then no light is transmitted.

Polarized light is used in some instrumentation, such as the *Absolute Distance Meter*.

Port

An **Input/Output port** or **I/O port** is a physical interface which enables a computer to communicate with peripheral devices such as a printers or external equipment such as theodolites.

A **serial port** or **COM port** transfers data in a serial fashion, i.e. individual data bits are transmitted one after the other. The ***Axyz*** system uses serial ports to connect theodolites and Total Stations to the controlling

PC. PCs are typically provided with two COM ports which are often sufficient to enable a dual instrument system to be configured. To connect multiple devices and/or more than two instruments, an additional PC board must be installed which supplies additional serial ports.

A **parallel port** transfers several bits of data simultaneously, for example all 8 bits of a byte. This enables faster communication than a serial port. Printers are typically connected to the parallel port.

Perspective view

Example: Perspective view of cube

A 3-dimensional view of an object or scene. The view is similar to the image recorded by the human eye or a camera.

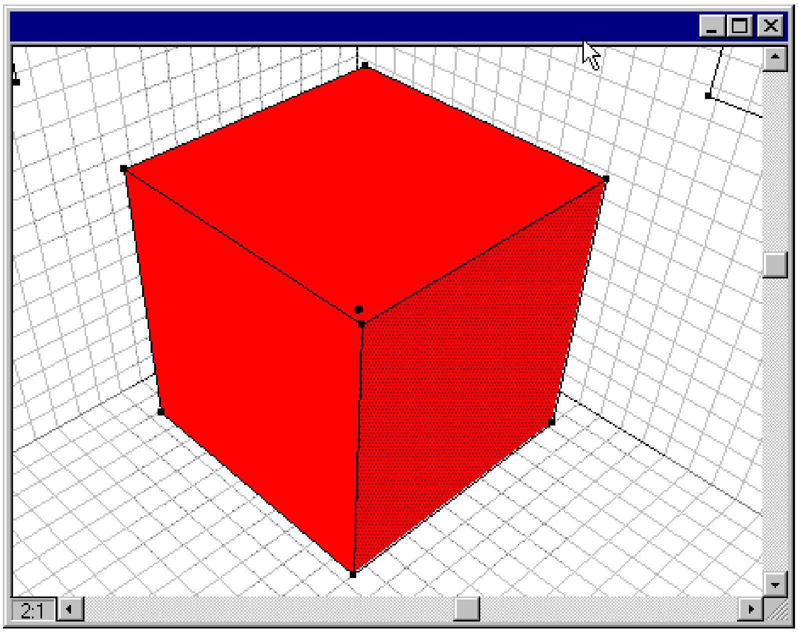
Typical properties of this type of view are:

- Parallel lines moving away from the observer appear to converge.
- Objects at different distances from the viewpoint are imaged at different scales.

For a perspective view generated by a camera, the representation of the object depends on the camera's position and focal length. A wide-angle camera emphasizes the effects of perspective, a telephoto camera reduces the effects.

See also *isometric view*.

Example: Perspective view of cube



View - Perspective.bmp

Precision

Indicates how well measurements of a particular quantity agree with one another.

- If precision is high the spread of values is small.
- If precision is low the spread of values is large.

Precision is a local effect and high precision does not guarantee that *accuracy* is also high.

Alternatives:
Repeatability

PSD

Short for *Position Sensing Device.*

Position Sensing Device (PSD)

An electronic **area array** sensor which can sense the position of a light spot imaged on its 2D surface. Electrical potentials are established in each direction (X and Y) of the surface. A light spot focused on the surface alters the balance of the potentials depending on its position from a **null-point** near the centre of the device. The output voltages effectively measure the location of the spot on the sensor.

This type of device can respond very rapidly to a change in position of the light spot and is used to control the mirror pointing in a laser tracker.

R

Random error

Random errors are small positive and negative variations in the value of a measurement which is repeated many times. This is a natural physical effect which cannot be completely eliminated by changing the design of the measuring system. Random measurement errors follow the *normal error distribution.*

Raw data

The *measurements* made by an instrument, corrected only by the instrument's own calibration parameters.

If the calibration parameters are accurate, the resultant values are those which would have come from a perfectly adjusted instrument and are subject only to random measurement error.

Redundancy

The number of measurements in excess of the minimum number required to calculate a particular set of parameters. For example, it is only necessary to measure the location of two points in space in order to calculate a straight line between them. If more points on the line are located, measurements to these are in excess of the minimum required.

Excess measurements are theoretically redundant, i.e. not required. However, because all measurement processes are subject to small *errors*, redundant measurements are valuable in revealing significant error sources and enabling optimal results to be calculated using the method of *least squares*.

Alternatives:
Degrees of freedom

Reference coordinates

Objects are manufactured to a particular design, often specified by a *CAD model*. Critical locations on the object must have particular coordinate values according to this design. These are known as reference coordinates and the associated point is a **reference point**.

Reference coordinates are used to *build* an object an object according to design or to *inspect* an object to confirm that it corresponds to the design. Reference coordinates are also used to calculate a *3D transformation* so that the reference coordinate system can be established and used during the measurement process.

Alternatives:
Design coordinates
Blueprint coordinates

Reference files

These are plain text files containing lists of *reference coordinates* and possibly other related data.

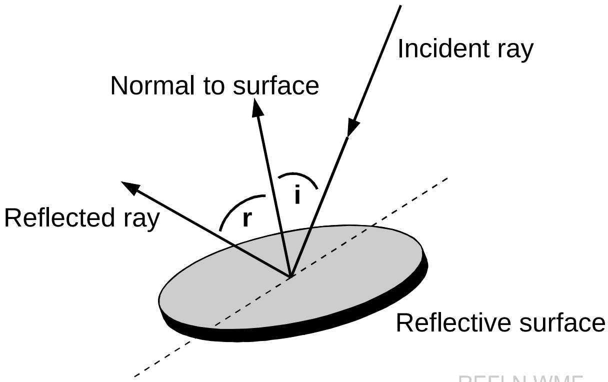
Reflection

Diagram: Plane reflection
Diagram: Plane reflection maths
Maths: Plane reflection
The deflection of a light beam back off a smooth surface such as a mirror.

When light strikes a smooth surface it is partly absorbed by the surface, partly reflected and possibly also partly transmitted through the surface. Polished metals typically mostly reflect. Liquid surfaces mostly absorb or transmit but will normally give some reflection. Mercury is a special exception as it is a liquid which reflects like a polished mirror.

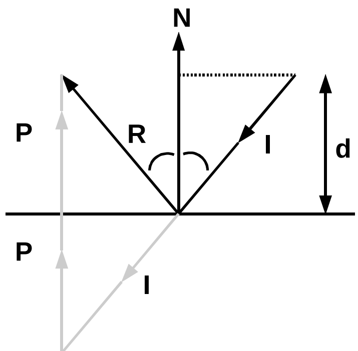
The properties of reflection at a plane surface are as follows:
If the incoming or **incident ray** makes an angle i with the normal (perpendicular) to the surface, and the **reflected ray** makes an angle r with the normal, then i equals r. Also the incident ray, reflected ray and normal all lie in the same plane.

Diagram: Plane reflection



REFLN.WMF

Diagram: Plane reflection maths



REFL-GEO.WMF

Maths: Plane reflection

Simple vector mathematics gives the vector equation for the reflected ray, derived from the incident ray and normal to surface.

Incident ray is **I**
Normal vector is **N**
Reflected ray is **R**

From the additional construction it can be seen that:

R = **I** + **P** + **P** = **I** + 2 **P**

P = d **N**	where d is the dot product of **I** and **N**, i.e.
d = **-** (**I . N)**	(negative value because of the directions of **I** and **N**)

hence

R = **I** – 2 (**I . N) N**

Refraction

Diagram: Refraction and dispersion

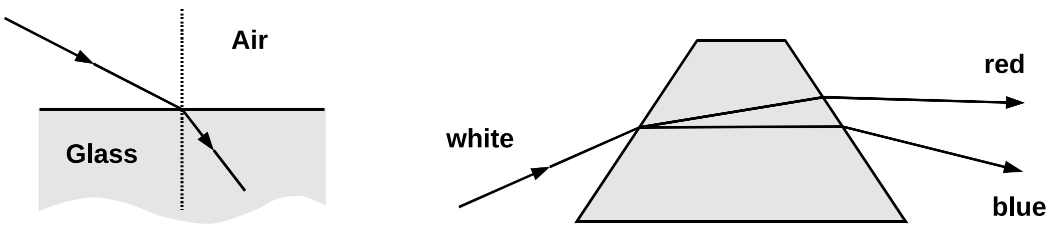
The deflection of a light beam when it passes from one transparent medium to another, for example from air to glass.

The effect is caused by *light* having different speeds in different media. Except in a vacuum, the speed of light depends on its frequency (colour).

The effect is quantified by the *refractive index* of the medium for light of a specified frequency.

The **dispersion** of white light into its constituent colours by a glass prism is a well known example of the differing amounts of refraction in the same transparent material. Dispersion for a particular material is quantified by the difference in refractive index for two particular red and blue frequencies. It is this effect which gives rise to chromatic *aberration* in lenses.

Diagram: Refraction and dispersion



Monochromatic refraction

Dispersion of white light by a prism

REFRN.WMF

Refractive index

Diagram: Geometry of refraction

Maths: Geometry of refraction

The ratio (n) of the speed of *light* in a vacuum (c) to the speed of light in the medium under consideration (v).

$n = c / v$

The value is always greater than 1 since light travels fastest in a vacuum.

The index quantifies a particular material's property of *refraction* and is different for light of different frequencies (colours). It is a critical parameter to be determined since the speed of light determines its wavelength according to the formula:

speed = (frequency) x (wavelength)

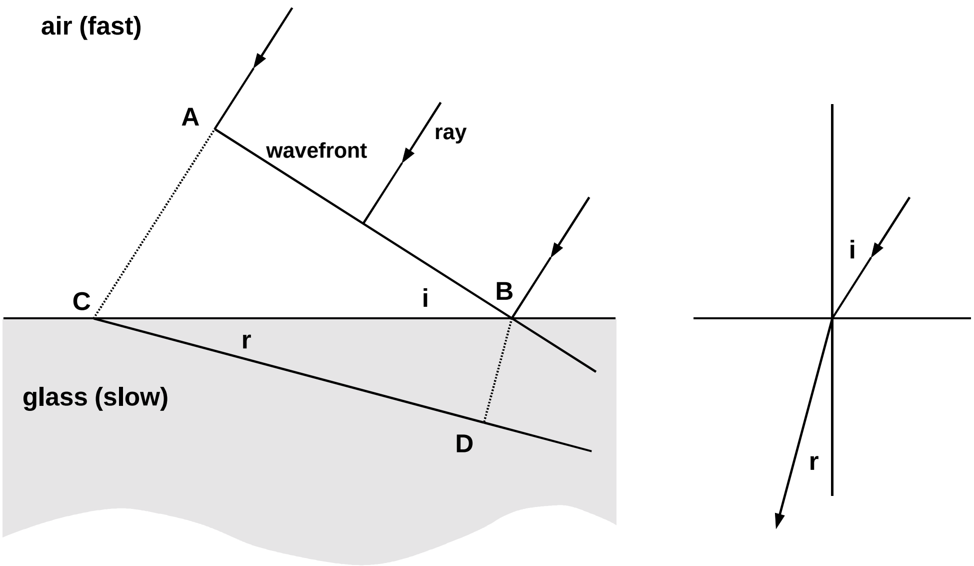
For accurate distance measurement the wavelength must be accurate.

The effect is significant for measurement in air which, at different temperatures and pressures, refracts light differently. For accurate measurements with lasers environmental conditions must therefore be monitored very carefully.

Alternatives:

Index of refraction

Diagram: Geometry of refraction



Refraction due to different speeds of light in different media

REFR-GEO.WMF

Maths: Geometry of refraction

The diagram shows a narrow bundle of rays which are effectively parallel. Perpendicular to the rays is the wavefront of the light. The light is travelling from air into glass.

In the time T it takes a ray to go from A to C, the ray at B reaches D. Because the speed of light in glass is slower than in air, distance BD is less than distance AC and the wavefront is turned through an angle.

If the speed of light in air is S1 and in glass S2, the refractive index n is given by:

n = S1 / S2

If the incident rays make an angle i and the refracted rays make an angle r with the normal vector to the air/glass surface, then refractive index n depends on i and r as follows:

AC = S1 x T, hence S1 = AC / T
BD = S2 x T, hence S2 = BD / T

n = S1 / S2, i.e.
n = AC / BD

This can be written as:

n = (AC/CB) / (BD/CB) = sin (i) / sin (r)

The refractive index is also therefore given as the ratio of the sine of the angle of incidence divided by the sine of the angle of refraction.

Note
When entering a slower medium, light is refracted towards the normal.

Refractometer

An instrument which measures the *refractive index* of a substance such as glass or a medium such as air.

Relative orientation

A relative orientation does not make use of *control points* and the coordinate system is initially arbitrarily defined by the first station processed, which is the lowest numbered station. Choosing the option for a *balanced station network* will cause the origin to drift slightly away from this initial position.

Alternatives:
Local orientation

Resection

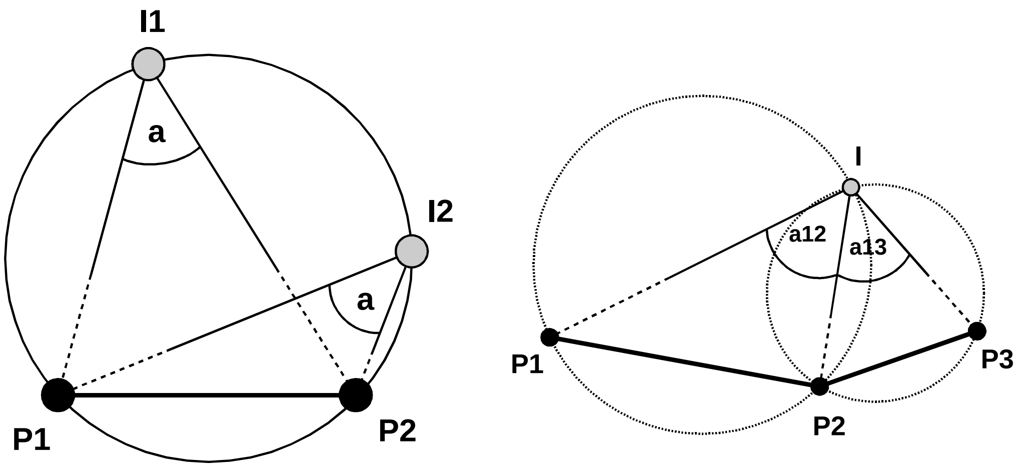
Diagram: Horizontal resection
Maths: Horizontal resection
Diagram: Ambiguity in 3D resection
Maths: Ambiguity in 3D resection

Resection is a technique of locating an instrument station in an existing coordinate system or finding the relative position of an instrument and an object.

It makes use of pointings only, defined by theodolite angles or camera image coordinates. It requires a minimum of 3 pointings to targets with known coordinates in an existing coordinate system or, equivalently, the local coordinate system of an object. The result is the instrument's position and tilt with respect to the coordinate system. If a specific object supplies the local coordinate system then this is easily interpreted as locating the object with respect to the instrument.

Alternatives:
Space resection

Diagram: Horizontal resection



Principle of resection RSCT-HOR.BMP

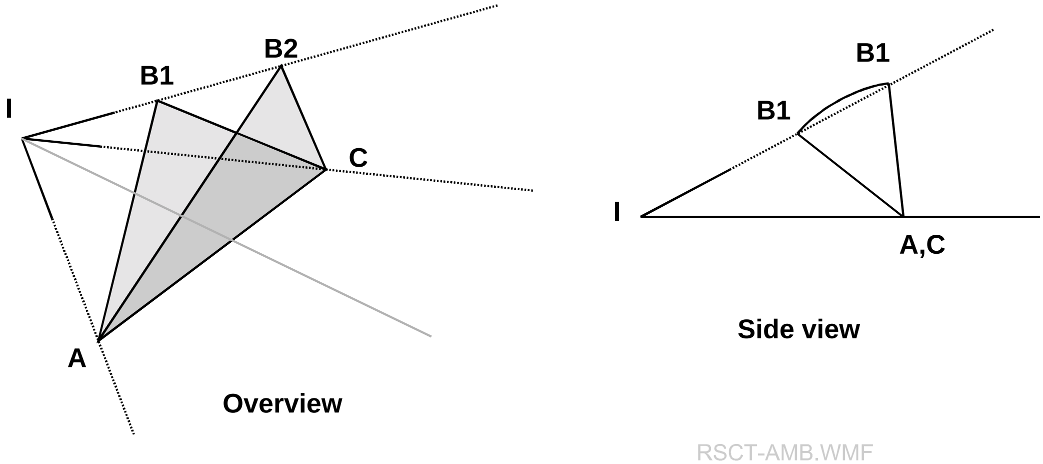
Maths: Horizontal resection

Resection originates in mapmaking where surveyors can **resect** their location in a horizontal plane by making theodolite pointings to 3 existing survey stations.

Any two pointings give the subtended angle between the stations. The **Apollonius' theorem** proves that all points on a circle through the two target points and measurement point subtend the same angle, i.e. pointings to two existing stations locate you on a particular horizontal circle.

Measurement to the third target provides a second circle and the intersection of both circles is the current location.

Diagram: Ambiguity in 3D resection



Maths: 3D resection

The concept of horizontal resection in 2D is readily extended to 3D. Three target points will again provide a location for the instrument but there are up to 4 possible locations. The diagram shows an easily understood special case where rotation of a 3 pointed object will produce the same subtended space angles at instrument position I for two different object positions B1 and B2. The issue is resolved in practice by measuring to a 4th. point on the object.

Residual

Residuals are the difference between a modelled value of a measurement and what you actually measure.
The least squares method finds a model which minimizes the sum of the squares of the residuals. The residuals therefore indicate how well a model of a situation fits the measurements.

Resolution

<u>1) Relating to encoders</u>
The resolution of a measuring component such as an angle encoder is the smallest incremental change which it can deliver. Resolution should be

higher than the expected measurement accuracy so that the measurement is not degraded by an inefficient encoder.

2) Relating to optics
The resolution of an optical system such as a telescope is a measure of its ability to reproduce fine detail in the image. Fine detail implies a sharp image and this contributes to a high quality pointing for both manual observation and electronic imaging.

3) Relating to digitized images
Images recorded electronically are divided into individual picture elements. The greater the number of elements in a given part of the image, the greater the digitized resolution.

Retro-reflector

Photo: Retro-reflective tape targets
Diagram: Target thickness and reflector offset
A retro-reflector is a passive material or device which reflects incoming light back along the same direction.

Retro-reflection is a common requirement for *electromagnetic distance measurement (EDM)* in which the transmitting device must have a return signal for comparison. A strong return signal can be provided by retro-reflective material forming a flat *target*.

Similar material is also used in industrial photogrammetry to provide very bright target points for flash illumination. In this case a special adhesive tape is used as the target material.

For optimal return signals, retro-reflectors are arrangements of mirrors such as *corner cubes* or glass elements such as *cat's-eyes*. Such a retro-reflector may be mounted in a spherical housing and known as **spherically mounted retro-reflector** or an **SMR**.

SMRs can be used to measure surface points by locating the reflector when it contacts the surface. Here the measured reflector point is offset from the surface and this **reflector offset** must be taken into account. Reflective target material can also generate an equivalent **target thickness** offset. The offset problem can be solved by use of a *surface reflector*.

Alternatives:

Reflector

Photo: Retro-reflective tape targets

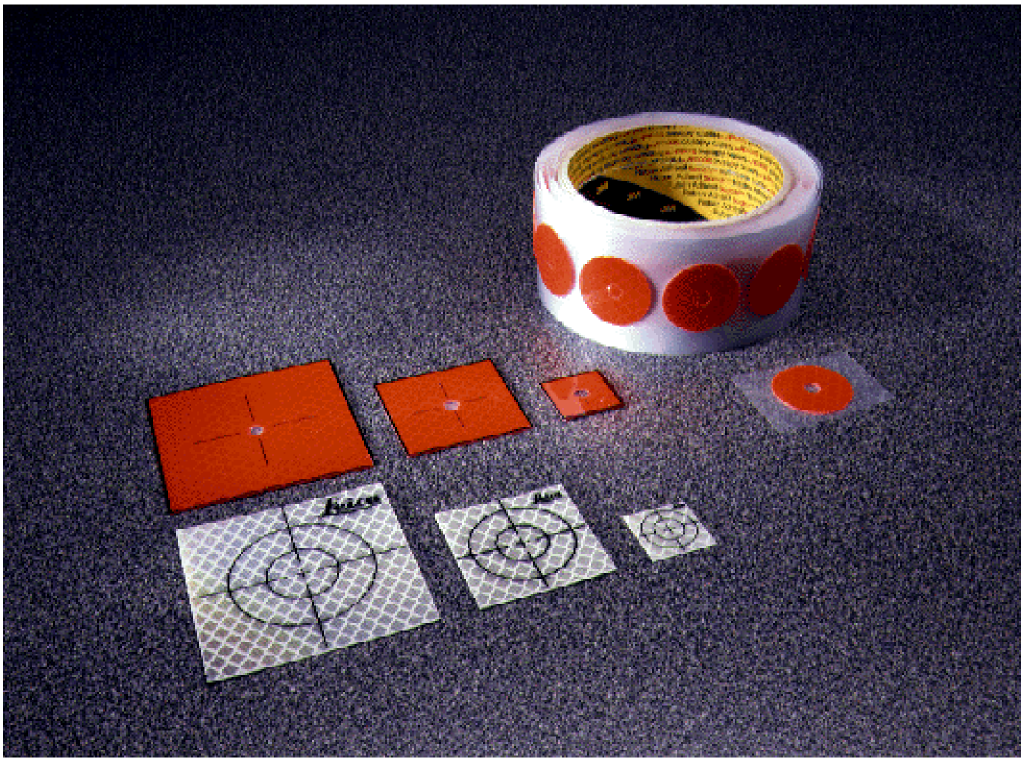
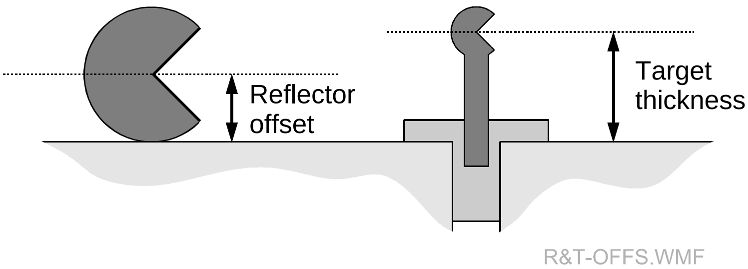


Diagram: Target thickness and reflector offset



Right hand rule

Diagram: Right hand rule
Diagram: Rotation of right handed axes
Diagram: Rotation of left handed axes
The right hand rule defines the positive direction for rotation about an axis. It can be visualized in several ways.

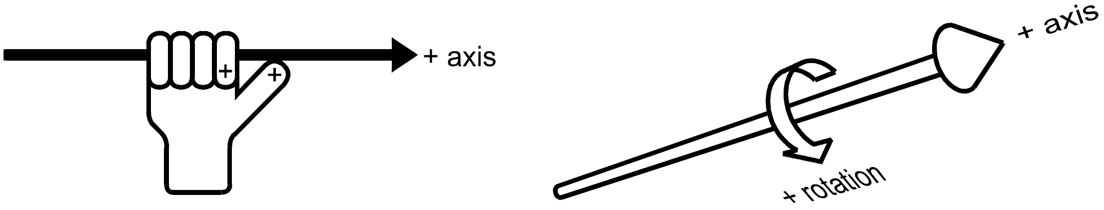
The first diagram illustrates the rule. Imagine you grip the axis in your right hand with the thumb pointing towards the positive direction of the axis. The curl of your fingers towards the tips then shows the positive direction of rotation.

Alternatively, imagine inserting a screw into a piece of wood. The direction of movement into the wood is the positive direction of the axis and the direction in which the screwdriver rotates is a positive rotation.

Note that this definition is not linked to **right and left handed axes** and is simply a way of defining a positive angular direction about a single axis.

The second diagram shows the effects of positive rotations on right handed coordinate axes.

Diagram: Right hand rule

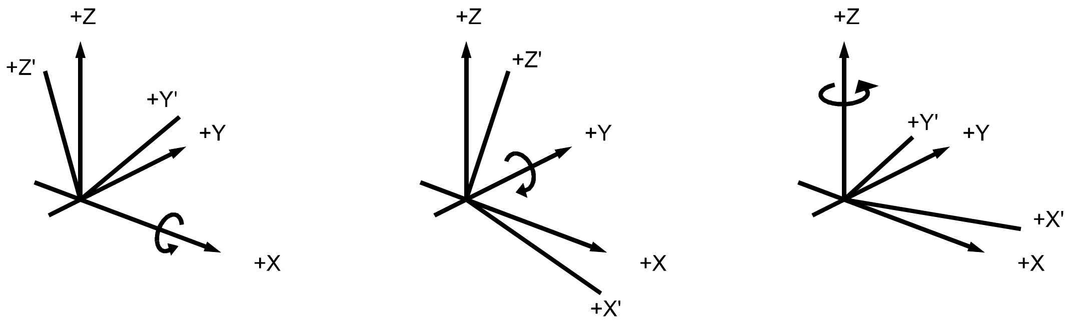


Right hand rule for determining the positive direction of rotation about an axis

RH-ROTNa.WMF

Diagram: Rotation of right handed axes

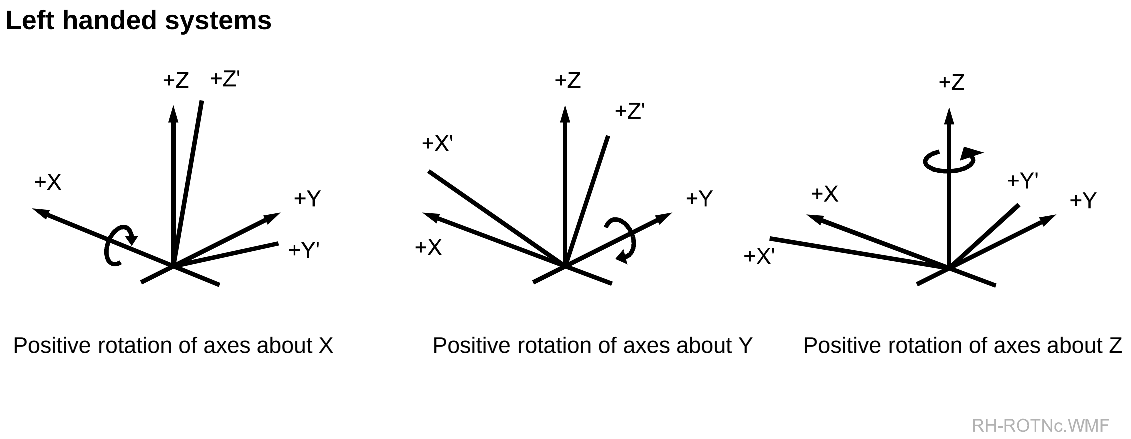
Right handed systems



Positive rotation of axes about X　Positive rotation of axes about Y　Positive rotation of axes about Z

RH-ROTNb.WMF

Diagram: Rotation of left handed axes



RMS

Short for *Root Mean Square.*

Root Mean Square (RMS)

The square root of the arithmetic mean of the squares of a set of numbers.

To be meaningful, the RMS is normally applied to numbers relating to the same physical quantity or similar quantities with the same units, e.g. angles, distances or coordinate offsets. Typically it is applied to error values.

The Root Mean Square (RMS) error is derived from a set of measurement residuals produced by a least squares analysis such as a bundle adjustment or shape fit.

The RMS value provides a single quality figure in the units of the measurement concerned. It is an estimate of the spread of the measurements and/or an estimate of the closeness of a fit.

A simple mathematical definition of the RMS value for N residuals v_1 .. v_N is

$$RMS_{resid} = \sqrt{\frac{\sum_{i=1}^{N} (v_i)^2}{N}}$$

Rotation matrix

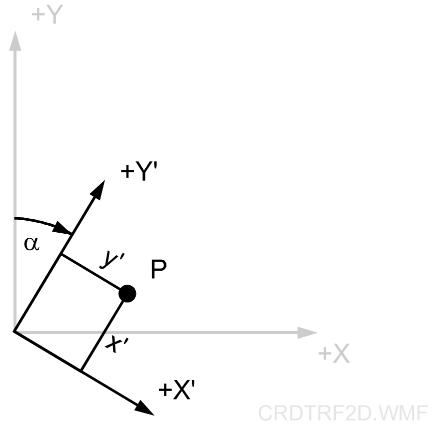
Rotation of axes in 2D space

A rotation *matrix* implements the *rotation parameters* which will either rotate an object into a new position or rotate the axes of the coordinate system to define a new system of coordinates.

Many different combinations of individual rotation parameters can represent the same angular orientation in space. The rotation matrix in 3D space is a 3 x 3 matrix of elements, each of which is some mathematical function of the underlying rotation parameters. A different function applies depending on which parameters are currently in use. However the actual numerical value of each element is the same, regardless of the configuration of rotation parameters.

See the detail box for a simple example of a 2D rotation of axes.

Rotation of axes in 2D space



A simple 2D case illustrates how coordinates are transformed by a rotation of axes. There is only one rotation parameter in this case, α.

To transform values from the old coordinate system (x,y) to the new (x',y'):

$x' = (x) \cos(\alpha) - (y) \sin(\alpha)$
$y' = (x) \sin(\alpha) + (y) \cos(\alpha)$

The rotation matrix to be applied to the (x,y) values in this case is:

$$\begin{vmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{vmatrix}$$

Rotation parameters

Diagram: Rotations Roll, Pitch and Yaw
Diagram: Rotation order
Diagram: Rotation axes
Diagram: Rotations not unique

A rigid object has a spatial position defined not just by its location but also by its rotational components, such as **roll**, **pitch** and **yaw** in an aircraft. Shifting and rotating an object with respect to a fixed coordinate system is also equivalent to holding the object fixed and moving the coordinate system. Rotations are therefore components of both ***orientation parameters*** and ***transformation parameters***.

There are many different ways of defining the rotational components. For example, any angular change to an aircraft could also be defined by specifying a rotational axis through it and then a particular rotation about that axis. The axis of rotation requires two parameters, such as horizontal and vertical angles, to define its direction. The rotation about the axis is a third parameter.

In fact, 3 rotational parameters are the mathematical minimum to define any particular angular change. If more than 3 are applied to any object, it is always possible to find an equivalent 3 which will achieve the same result.

Rotations have properties important for understanding their meaning.

1) Order of rotation is important
The diagram shows two 90° rotations applied to a die. The result is different depending on whether the rotations are applied first about the Y axis, then the X, or vice versa.

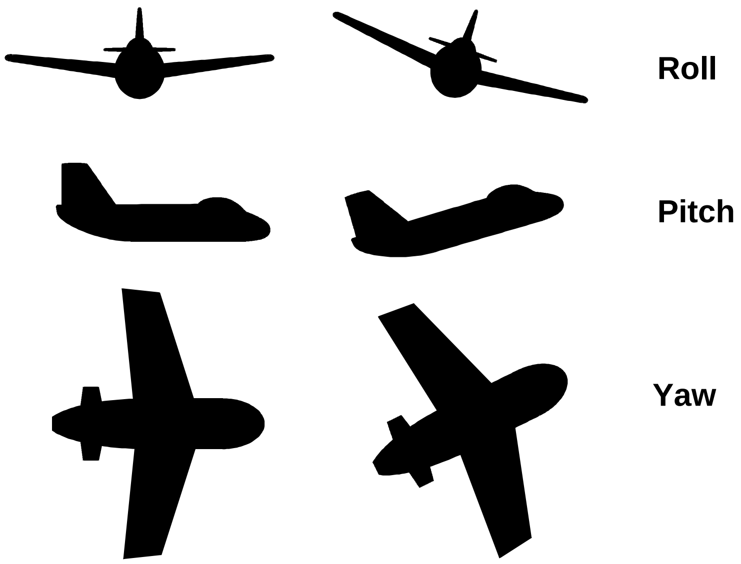
2) Axes of application is important
It is convenient to use axes fixed in space as well as axes fixed to an object. It must be clear which are used as results will be different. The diagram shows 90° rotations applied first about Y then about X using axes fixed in space, then the same rotations applied first about y then about x using axes fixed to the object.

3) Standard combinations may not give unique results
Normally a standard set of rotational parameters provides 3 unique values to effect a particular net rotation. Unfortunately in some special situations this is not the case. The diagram shows a commonly used set of rotations, first about Z, then Y, then X. Different values for Z and X are possible to achieve the same result. This caused by the 90° rotation about Y. In fact, there are an infinite number of combinations of Z and X rotations. This causes problems in some analysis functions, such as the *bundle adjustment* which has to calculate rotational parameters and may fail to do so if they do not give a unique result. The problem can be solved by switching to a different configuration of parameters such as a change in order to rotations about Z, then X, then Y.

Rotational parameters are applied mathematically through a *rotation matrix*.

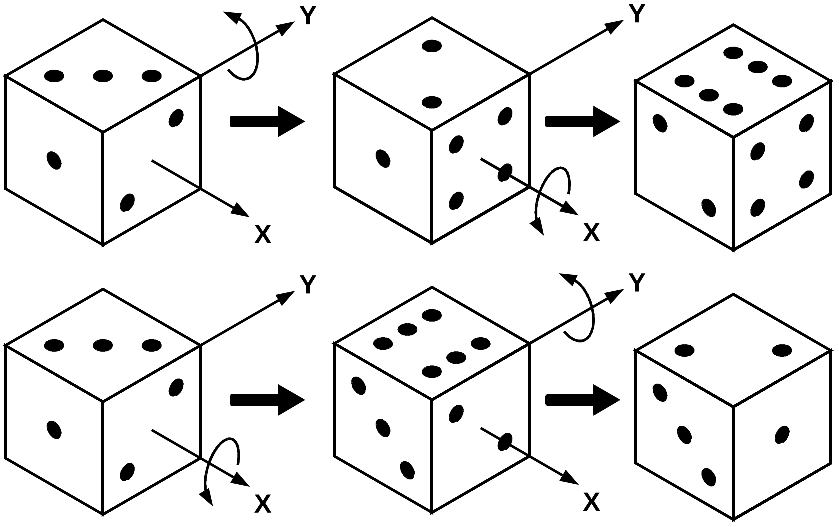
Alternatives:
rotational parameters
tilt parameters

Diagram: Rotations Roll, Pitch and Yaw



AIRANGL.WMF

Diagram: Rotation order



ROPM-ORD.WMF

Diagram: Rotation axes

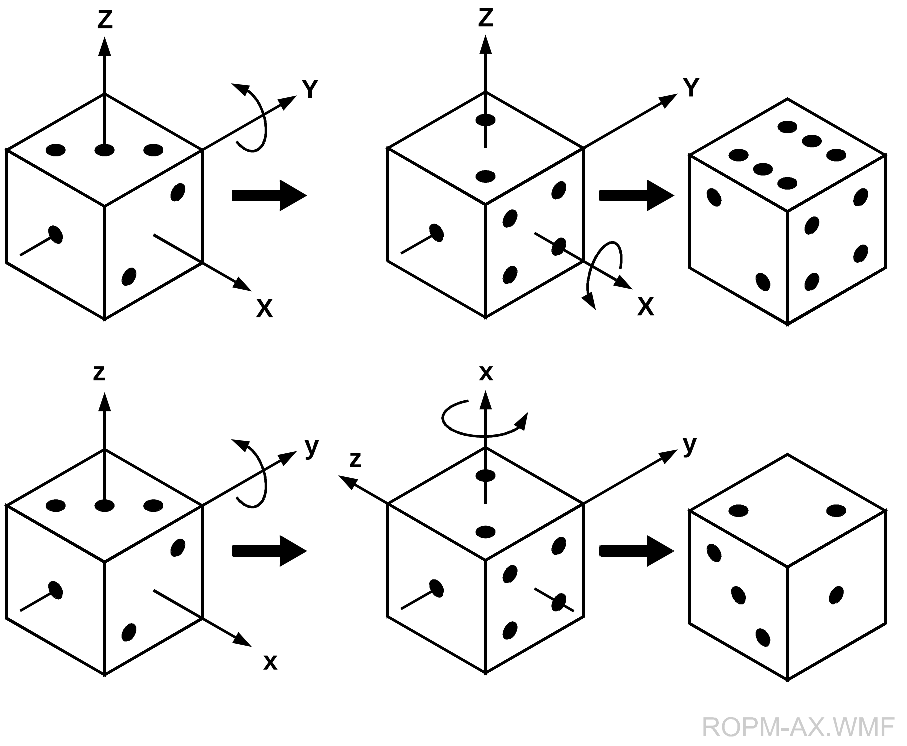
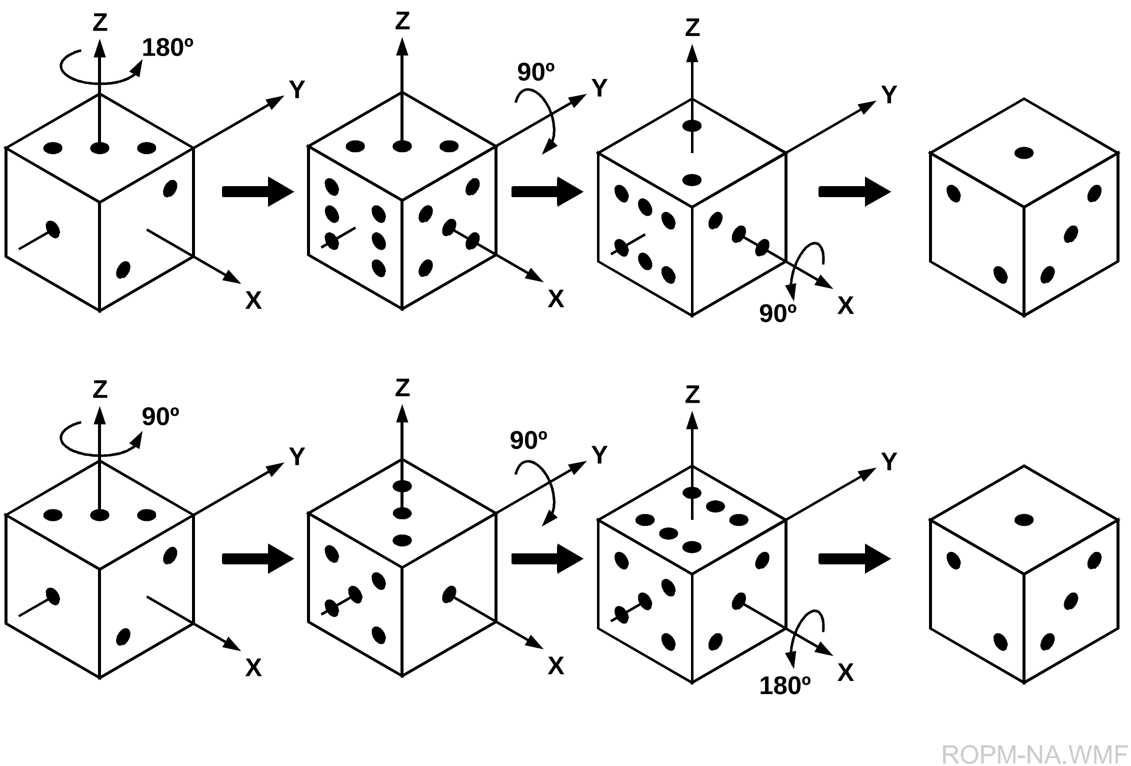


Diagram: Rotations not unique



S

Scale bar

A rigid calibrated bar which provides two or more target locations. Between pairs of target locations the distance is accurately known. By measuring the separation and comparing it with the reference value, the operation of the measuring system can be checked.

Very often a scale bar has only two target positions.
For use with video cameras the targets are likely to be retro-reflective discs. For use with theodolites the targets are likely to be high-contrast 2D targets.
For use with laser trackers the bar may have holders for retro-reflectors or have spherical surfaces whose centres can be indirectly determined.

Scotchlite

Trade name for an adhesive, *retro-reflective* material manufactured by the 3M Company.

Set

Sets are data entities originally introduced to accommodate *tracker* data. Since the tracker operates dynamically it can generate large quantities of data but the items are often related.

> <u>Example 1</u>
> Tracking a reflector on the end of a robot as it moves on a programmed path. Here the path is the item of interest.
>
> <u>Example 1</u>
> Tracking a reflector scanned across the surface of a smooth object. Here the surface is the item of interest.

Both items of interest are defined by multiple recorded points or sets. There are two types of set.

A **measurement set** is a stream of continuous measurement triplets (horizontal angle, vertical angle, distance) to the current reflector position from a single tracker and represents the dynamic measurement of a moving reflector.

A **coordinate set** is a related group of coordinate values, typically (x,y,z) values, located within the measurement network. Normally it is created by converting a measurement set to object coordinates. For example, by correcting a measured surface scan to the actual surface points. It can also be manually created or imported from, say, an external CAD source.

Setup

1) Setup (noun)
The static arrangement of one or more *theodolites, Total Stations* or *trackers* currently connected to the controlling PC.

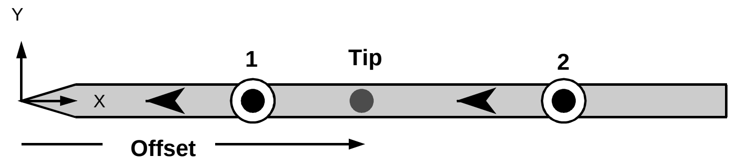
This arrangement of instruments does not necessarily define the complete measurement *network* but may only be a part of it. Several different setups may be required in order to completely measure an object.

2) set up (verb)
To place and connect an instrument ready for use.

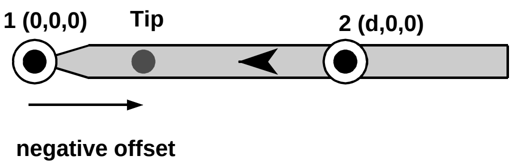
Sine bar

Diagram: Sine bar
A sine bar is an American term for a type of *hidden point device* which has two targets and a hidden point lying between the targets. It is typically inserted into a gap where a central position between the sides is the critical point of interest.

Diagram: Sine bar



A sine bar requires an offset to place the tip between the targets



Typical Sine Bar definition

HIDPT-F.WMF

Single Point Solution

Diagram: Single point triangulation
Diagram: Multiple polar location

The Single Point Solution takes all angular pointings and polar measurements to a single target point and finds an optimal 3D location for the target which is a **best fit** to the measurements.

A best fit is required as pointings do not always exactly intersect and multiple polar locations do not always exactly lead to the same position.

Diagram: Single point triangulation

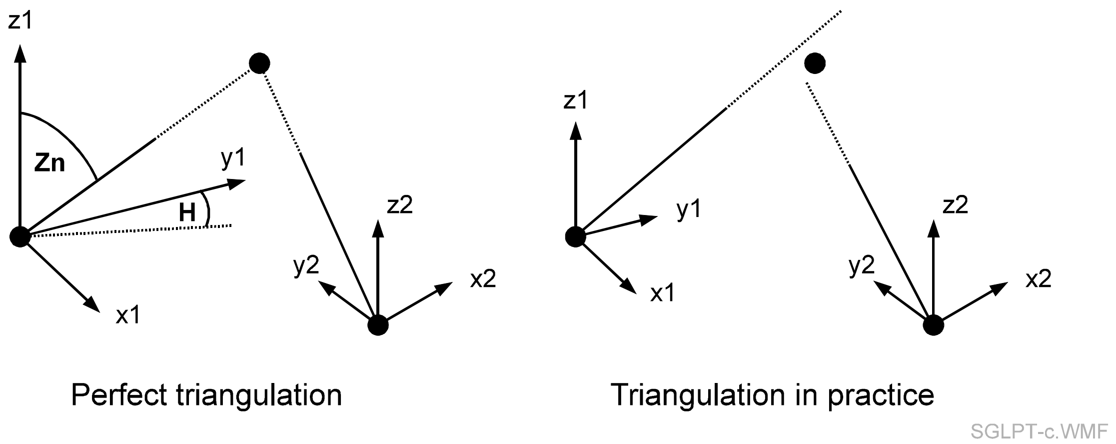
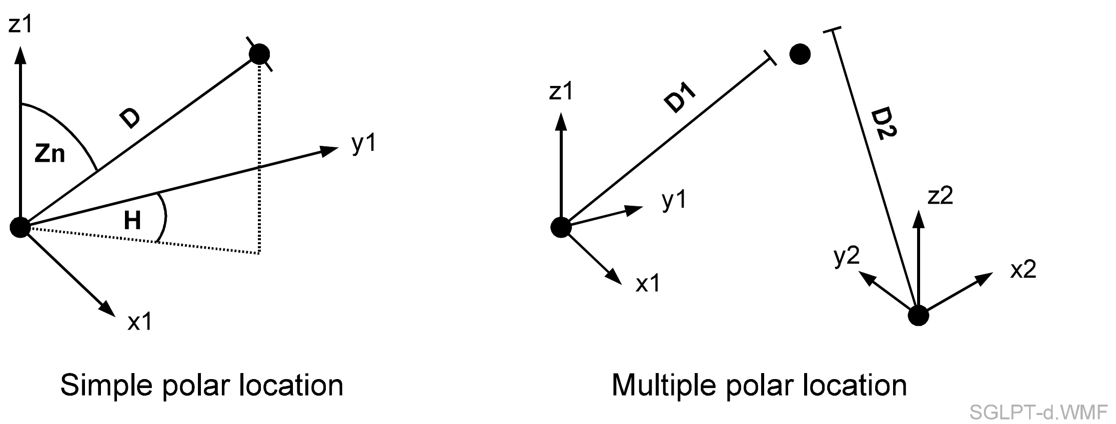


Diagram: Multiple polar location



SMART

Short for System for Mobile Angle and Ranging to Target.

This was the first commercial version of Leica's laser *tracker*. It was manufactured by *Kern* Swiss.

SMR

Short for **Spherically Mounted Retro-reflector**.

SPACE

Short for System for Positioning and Automated Coordinate Evaluation.

This was an automated *triangulation* system based on remotely driven motorized theodolites and electronic imaging of the telescope's field of view. It was manufactured by *Kern* Swiss. (No longer in production.)

Startup

startup (noun)
The initial part of starting up a physical or software process.

start up (verb)
To initiate a physical or software process.

Station

In ***Axyz*** a station is a particular location of a specific instrument. During a measurement job the same instrument can be moved to different locations and therefore occupy more than one station. Different stations may be very close together, for example when an instrument is accidentally disturbed.

Stereoscopy

Stereoscopy is a technique of using two photographic images to visualize an object in 3 dimensions.

Stereoscopic photographs or images, which form a **stereo pair**, are taken from two slightly different positions with the camera axes parallel or slightly convergent. This simulates the case of viewing objects by eye. If the left and right image are each separately viewed by the left and right eyes, using a **stereoscope** or one of its more sophisticated derivatives, then the brain will fuse the images together and generate a 3D image of the object.

This 3D image can be measured by moving a measuring mark across each image. The mark itself is also fused into a 3D mark, appearing to float above or below the object's surface. When brought into contact with the surface the same target point has been located in each image.

Well established techniques are available to automate this process in the case of electronic images.

For measurement of surface form, the method can avoid the need to place targets on object surfaces, relying instead on the object's natural surface texture. However the geometry of the situation is not optimal and it would not normally be used where high 3D accuracy was required.

STM

Short for **Single Theodolite Module**, one of the ***Axyz*** software modules.

Surface reflector

Principle: Surface reflector
Photo: Surface reflector
Diagram: Reflector offset (and target thickness)
A surface reflector is a *retro-reflector* mounted in a special target fixture so that the location of a **virtual image** of the reflector is determined.

The surface reflector is primarily designed for use with the *laser tracker*. Often the target point of interest is a point on the surface of the measured object but measurement can only be made to the reflector centre which is offset from the surface.

The surface reflector has a plane mirror which creates a virtual image of a normal retro-reflector. A probe tip behind the mirror is positioned so that the tip is at the centre of the virtual reflector. The tracker's laser beam is directed at the reflector via the mirror and therefore appears to locate the virtual reflector. By touching the probe against a surface point of interest, measurement is effectively made directly to that point.

Principle: Surface reflector

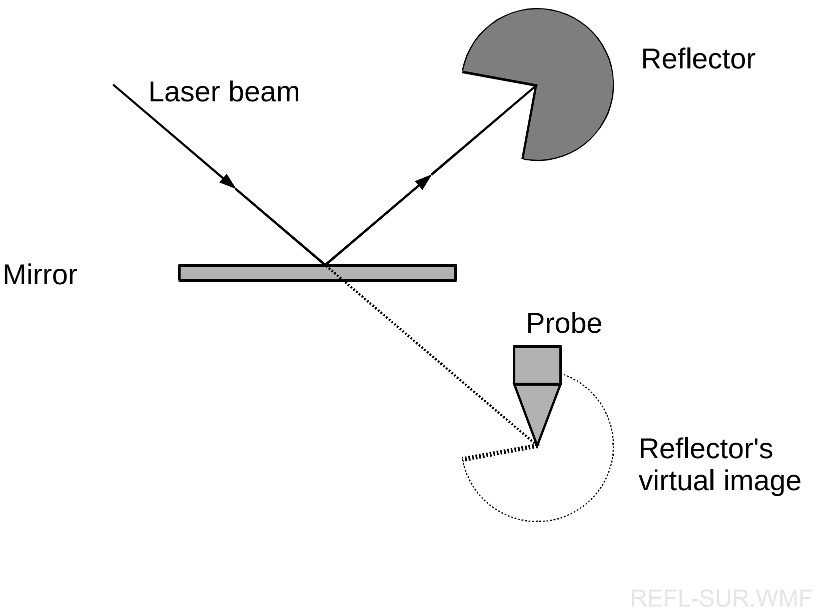


Photo: Surface reflector

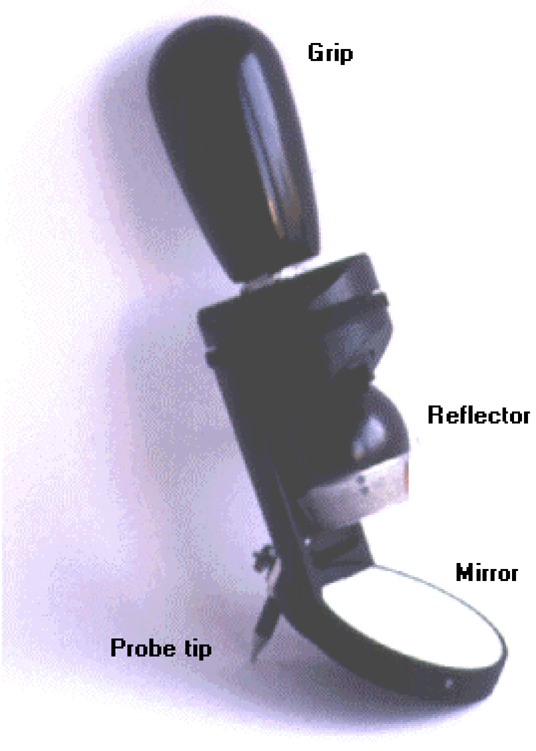
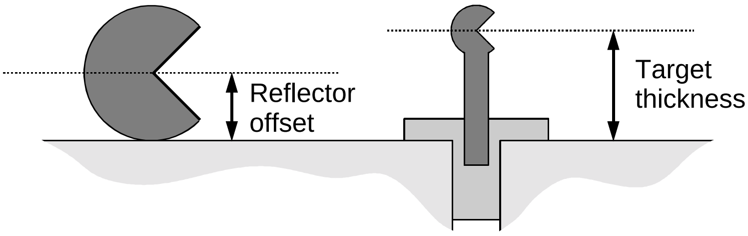


Diagram: Reflector offset (and target thickness)



Systematic error

Systematic errors follow a definite pattern caused by some particular physical effect. For example an electronic distance meter may give readings which are consistently too low or too high if the incorrect carrier frequency has been applied.

Systematic errors can be corrected by software compensation.

T

Tachymeter

Tachy- or tacheo- derives from the Greek meaning speed. The tachymeter offers a fast means of measuring distances and directions.

It is more commonly known as a *Total Station.*

Alternatives:
Tacheometer

Target

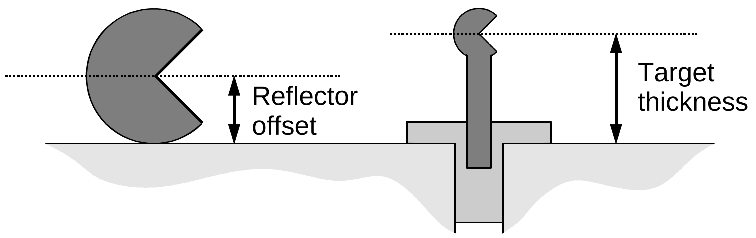
Diagram: Target thickness and reflector offset
Object points of interest are often identified by a specially manufactured precise marker stuck to the object's surface or inserted into a feature of interest, such as a drilled hole whose centre is to be measured.

Examples:
Retro-reflective adhesive disks
Bull's-eye targets

A target may also be a temporary mark such as a laser spot projected onto the object's surface by a theodolite or Total Station equipped with a **laser eyepiece.**

Targets are often physically offset from the object feature they mark. Even thin adhesive targets may have a significant thickness. Significant offsets must be taken into account in achieving the highest measurement accuracy. For targets this offset is generally known as **target thickness**. Measurements to reflectors show an analagous effect known as **reflector offset**.

Diagram: Target thickness and reflector offset



R&T-OFFS.WMF

TBR

Short for **Tooling Ball Reflector**.

Telescope

Diagram: Theodolite telescope cross section (detailed)
Diagram: Theodolite telescope cross section (simplified)
Concept: Theodolite telescope operation (simplified)
Photos: Alignment telescopes for optical tooling
In optics, a telescope is an arrangement of *lenses* or mirrors which provide a magnified image of a target object. Telescopes can also be constructed to utilize electromagnetic waves outside the visible spectrum. Radio telescopes, for example, use parabolic mirrors to provide magnified images of radio sources in outer space.

An optical telescope is provided with a **reticle** (also known as a **graticule** or less commonly as a **reticule**) to define a specific viewing direction or **line-of-sight** in space. This is an arrangement of fine lines placed in one of the image planes which enables a particular image point to be identified. Modern optical instruments use lines formed on a glass surface. Old instruments used fine hairs or wires, typically to form a cross, hence the alternative names **cross hairs** or **cross wires**.

By mounting a telescope to rotate about two *orthogonal* axes, it forms the basis of *theodolites* and *Total Stations*.

The direction defined by the centre of the reticle would normally be co-incident with the optical axis of the telescope. In a perfect arrangement of lens or mirror elements this would be the axis of symmetry.

To focus on objects at different ranges, an internal (focusing) lens is normally moved. Manufacturing tolerances may cause small changes in the alignment of this lens as it moves, in turn causing small changes to the direction of the optical axis. In effect, the line of sight changes slightly on re-focusing. Since the line of sight is not constant this could lead to unacceptable errors in defining directions. **Alignment telescopes** are manufactured to keep this movement within a very small tolerance. Typically they are used in *optical tooling*, to define a straight line, but they have also been incorporated into theodolites to reduce pointing errors.

The photos show an alignment telescope for optical tooling. One is manufactured by Brunson and one by Taylor-Hobson (shown in use by an operator).

The diagrams show the lens arrangement and their concept of operation. Light from a target object enters through the **objective lens** which would, by itself, focus the light at image position P (see concept diagram). However the rays are diverged and focused onto the reticle by the **focusing lens,** for which a mechanical movement is provided. An **eyepiece** then magnifies the target image, overlaid with the reticle. Practical telescopes (see detailed cross section) additionally have an **erecting prism** which simply inverts the image so that it is the same orientation as the object.

Diagram: Theodolite telescope cross section (detailed)

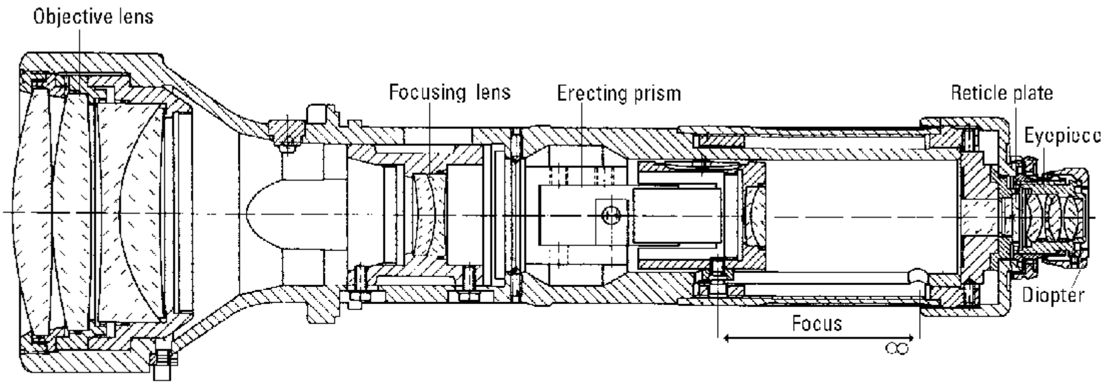
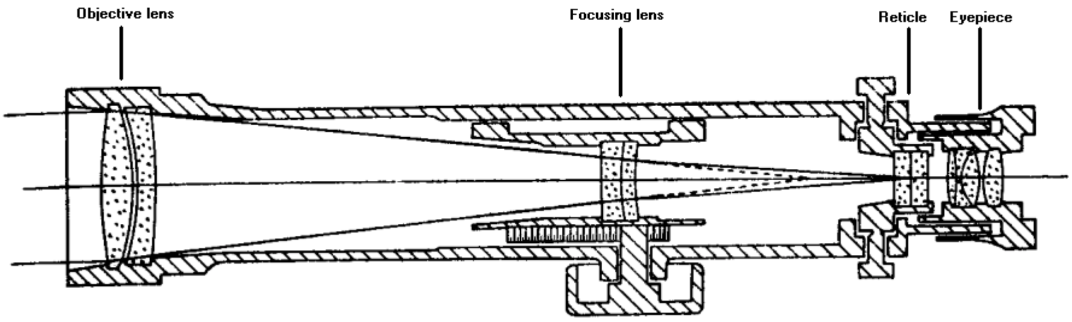
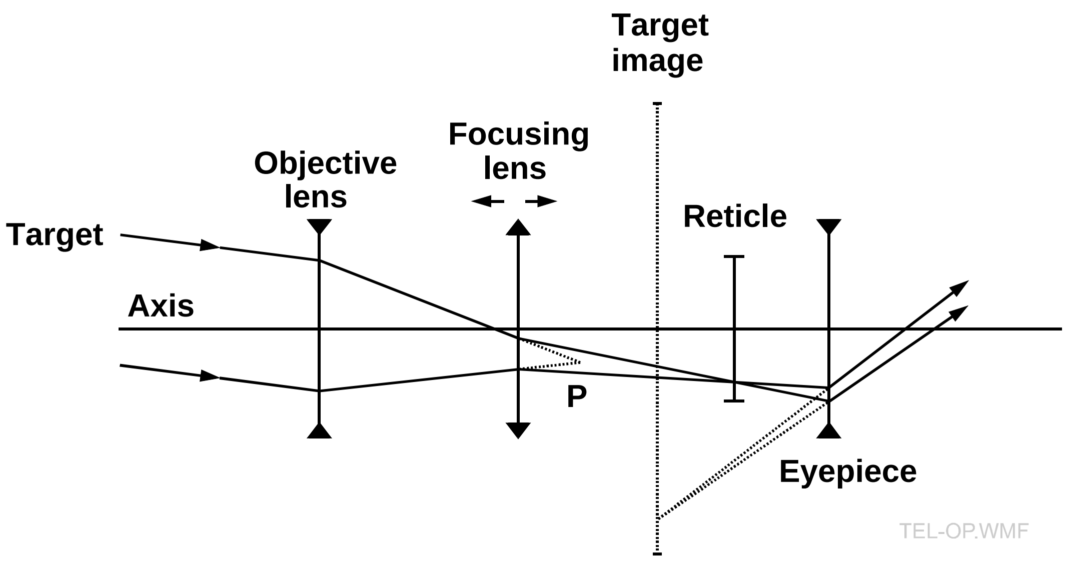


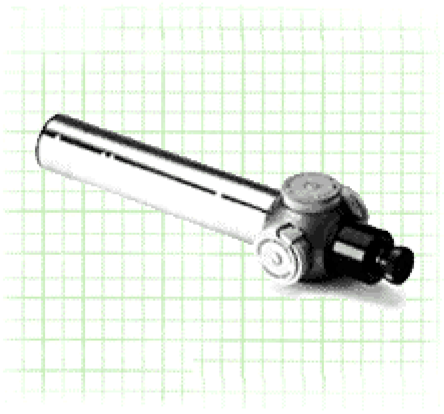
Diagram: Theodolite telescope cross section (simplified)



Concept: Theodolite telescope operation (simplified)



Photos: Alignment telescopes for optical tooling



Theodolite

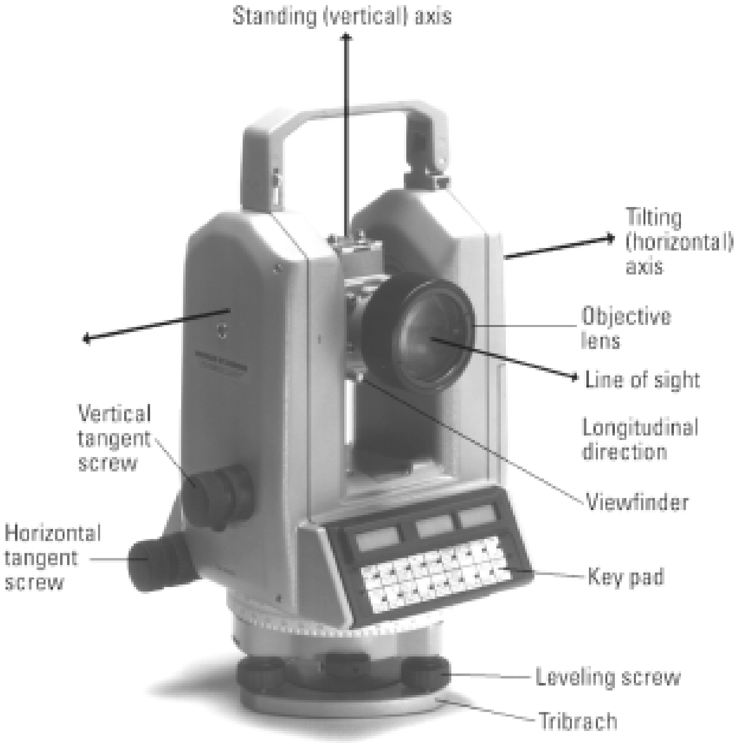
Photo: Theodolites
Photo: T3000 – labelled components
An instrument for measuring angles from a measuring station to a remote target point.

The pointing is made using a telescope which rotates about two intersecting orthogonal axes. The angles measured on these axes define the pointing.

The instrument may be accurately levelled so that its **primary axis** is vertical.

Photo: Theodolites

Photo: T3000 – labelled components



Thermal distortion

Table: Expansion coefficients for some common materials

Thermal distortion is the change in shape of an object caused by a change in temperature.

All materials expand and contract as the temperature rises or falls. For a wide range of materials this expansion has been quantified as the material's **coefficient of expansion**. This is typically defined as the change in length of a unit length of the material, for a one degree Celsius change in temperature.

Since different materials have different coefficients of expansion, a manufactured object composed of several materials will not uniformly change its shape when the temperature changes.

Expansion coefficients for some common materials

Material	**Coefficient of expansion**
Aluminium	22.5×10^{-6}
Steel	11.7×10^{-6}
Tungsten	5.0×10^{-6}
Invar	0.6×10^{-6} (approx.)
Carbon fibre	n/a

Tolerance

The extent by which a value should vary, defined by specified limits.

All measurement and manufacturing processes are subject to unavoidable *random error*, even when measuring and manufacturing systems are in perfect adjustment. To ensure that components fit together, critical locations and surfaces are assigned a tolerance with respect to their design or **nominal value**. The actual value is permitted to vary from nominal up to the tolerance limit.

In a measurement process the tolerance is usually related to the spread of random errors calculated or assumed for a particular parameter, such as the Z value of a flat surface. The tolerance is usually chosen as a figure either side of the estimated value which will cover most of the random measurement error and therefore most of the possible variations.

The spread of random variations is described by the *normal distribution* curve and its parameter, the standard deviation, σ (see *variance*). A quoted tolerance depends on what percentage of measurements lies within the tolerance limits:

- 90% lie within ±1.64 σ
- 95% lie within ±1.96 σ
- 99% lie within ±2.58 σ

Tooling ball

A precisely machined spherical surface whose centre provides a point of reference.

Tooling ball centres may be located by mechanical means, for example using the touch probe of a CMM. They can also be detected optically, for example by providing a light source on a theodolite telescope and sighting on its reflection in a polished tooling ball. The star-like image which results is very close to the centre, provided the light source is close to the telescope's axis and the ball is not too large.

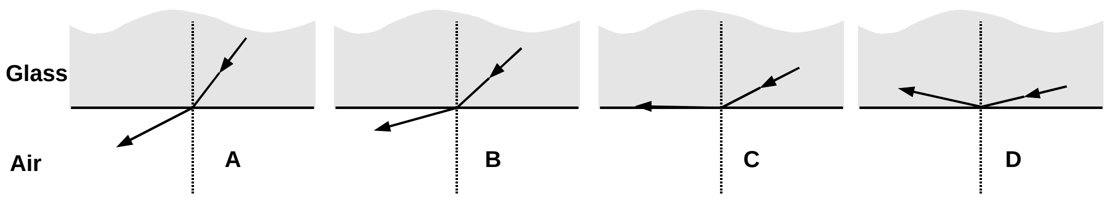
Total internal reflection

Diagram: Total internal reflection
Total internal reflection of light occurs when light travels from a dense medium such as glass into a less into a less dense medium such as air where its speed is higher.

At a certain angle the light will be *refracted* at the air/glass surface as indicated in (A). As the incident angle of the light changes in (B), the refracted ray moves closer to the surface. In (C) the refraction is such that the light emerges parallel to the surface. The incident angle in this condition is known as the **critical angle**. . Finally in (D) the incident angle is sufficiently large that the light is *reflected* back into the glass.

This property of light and materials is put to use in the *NIVEL* tilt sensor.

Diagram: Total internal reflection



REFL-INT.WMF

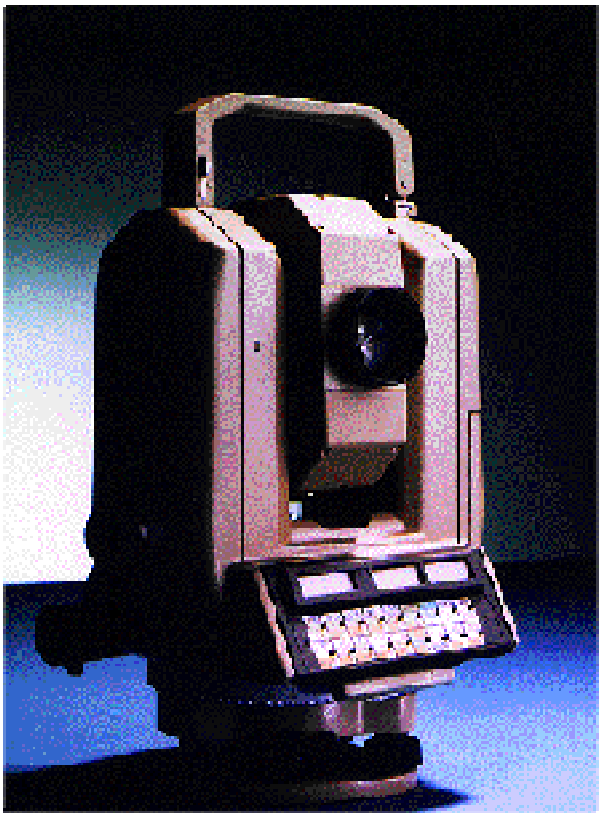
Total Station

Photo: Total Station - TC2002

A *theodolite* equipped with an *Electronic Distance Meter* (EDM) which enables it to measure distance along the line of sight.

Alternatives:
Tachymeter

Photo: Total Station - TC2002



TP

Short for **Tracker Processor.**

Tracker

Diagram: Components of tracker sensor
Diagram: Tracker sub-systems
Photo: Tracker

The tracker is a dynamic tracking laser interferometer. The instrument has an interferometer beam which is reflected off a mirror driven about two perpendicular axes and onto a target *retro-reflector*. If the reflector moves the return beam shifts laterally. This shift is detected and the mirror moved to bring the beam back on line again. In this way a tracking mechanism is established.

The angle and interferometer readings are continuously monitored and converted into 3D coordinates 1000 times a second, and this is the rate at which a moving reflector can be tracked in space.

Since an interferometer only measures a change of distance it must start from a known position. This is the **Home Point** or *Birdbath* which is provided on the instrument itself.

To avoid the need to re-initialize the distance after the beam is interrupted, some versions of the tracker are equipped with an *Absolute Distance Meter (ADM)* which can independently measure an accurate absolute distance to the reflector. ADM measurements are not dynamic and cannot track.

The tracker has three main subsystems:

1. A controlling PC known as the **Application Processor (AP)** is the interface between the operator and one or more tracker sensors. The AP communicates via a *Local Area Network (LAN)* with one or more **Tracker Controllers**
2. Each Tracker Controller has its own separate microprocessor, also known as the **Tracker Processor (TP),** and is responsible for controlling and reading a single tracker sensor.
3. The **tracker sensor** houses the actual measurement devices such as the *interferometer* and *angle encoders*. Each sensor is identified by its own **tracker number** which is the serial number of manufacture.

Within the sensor unit the rotating element containing the mirror is often called the **tracker head** .

For further information see:
Tracker alignment
Tracker alignment parameters
Tracker alignment techniques

Alternatives to "tracker":
Laser tracker
Tracking laser interferometer

Diagram: Components of tracker sensor

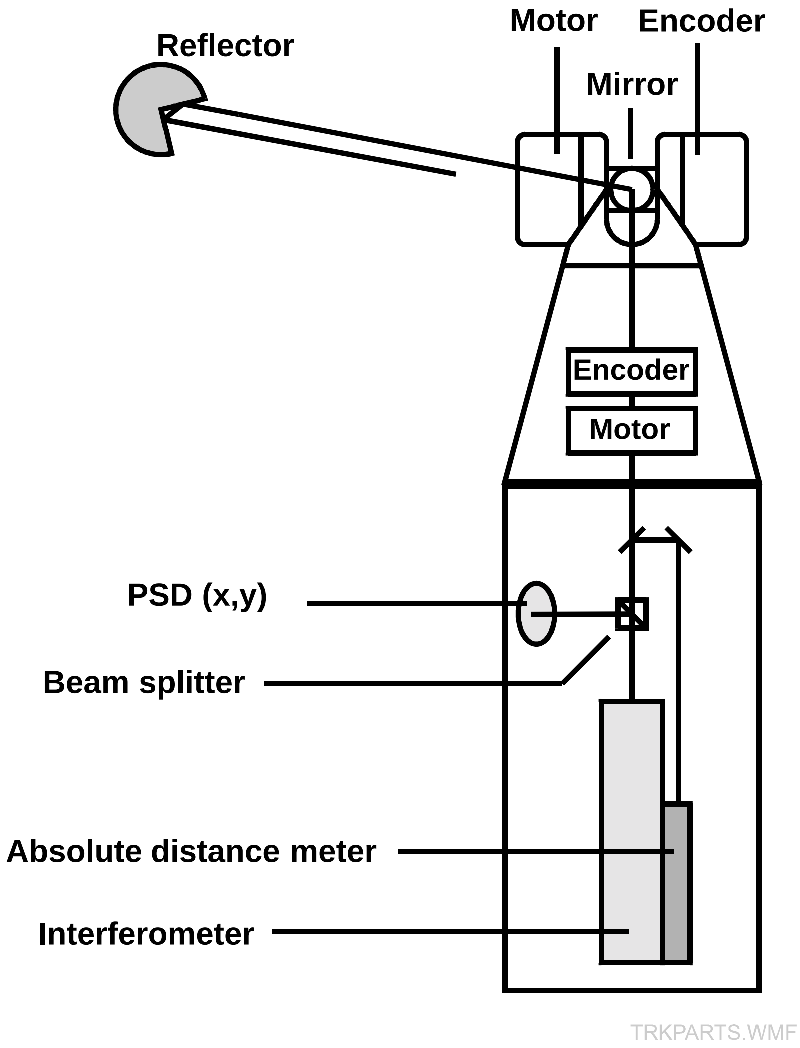


Diagram: Tracker sub-systems

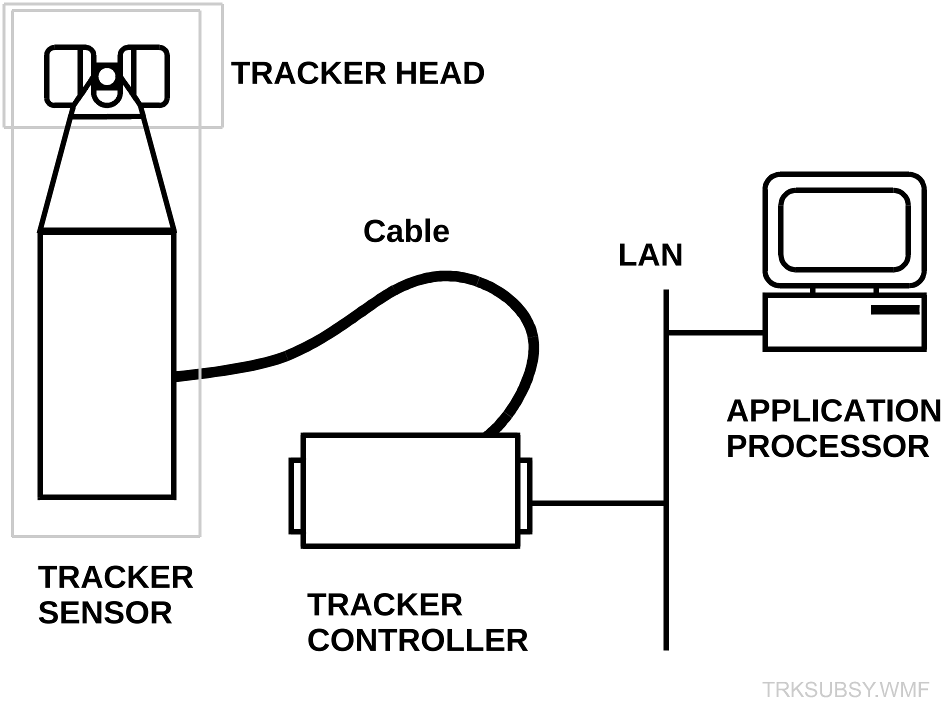


Photo: Tracker

Tracker alignment

For introductory information see *tracker*.

The tracker is a complex arrangement of components which should ideally be correctly aligned with respect to one another. For example, the laser beam should lie exactly on the primary axis of rotation (the standing axis).

It is impossible to manufacture the tracker exactly according to design. However it is possible to determine the residual errors in *alignment*. Using a mathematical model of the tracker, software compensation can be applied to the measurements so that they appear to come from a tracker whose components are perfectly aligned. Corrected measurements then only show small random effects.

This procedure does not involve a physical adjustment of the tracker's components to bring them into alignment.

For further information see:
tracker alignment parameters
tracker alignment techniques.

Alternatives to "tracker alignment":
Tracker calibration
Tracker modelling

Tracker alignment parameters

Vertical index error, transit axis tilt, mirror tilt, Beam tilt,
Transit axis offset, mirror offset, beam offset, cover plate offset,
Horizontal encoder eccentricity, vertical encoder eccentricity
For introductory information see:
tracker
tracker alignment

The **tracker alignment parameters** are the 15 parameters of the mathematical model used to correct measurements made by the tracker so that they appear to come from an exactly aligned instrument.

The tracker alignment parameters have a physical meaning as indicated in the diagrams. They are treated separately from parameters such as the *Birdbath distance*, which is also critical to the tracker's accuracy.

Various tracker alignment techniques are available to calculate the parameters. Three of the parameters can be calculated by a simpler technique which provides an intermediate update in a maintenance programme. These three are:

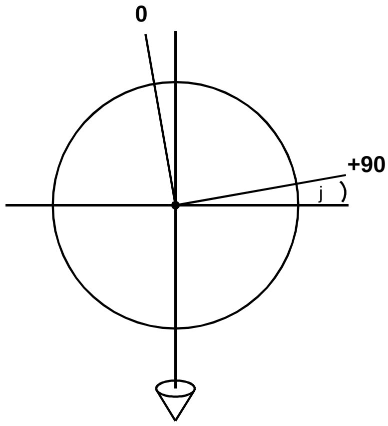
1. **Vertical index error**
2. **Transit axis tilt**
3. **Mirror tilt**

The remaining parameters are:

- **Beam tilt** (2 components)
- **Transit axis offset**
- **Mirror offset**
- **Beam offset** (2 components)
- **Cover plate offset** (2 components)
- **Horizontal encoder eccentricity** (2 components)
- **Vertical encoder eccentricity** (2 components)

For further information see:
tracker alignment techniques

Vertical index error, j



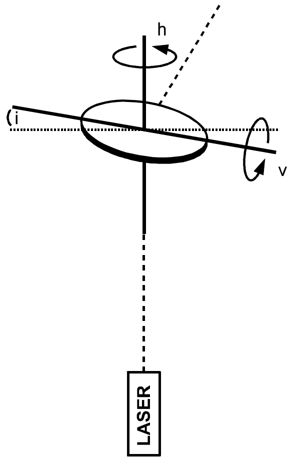
Vertical index error: j

The reading on the vertical circle should be 90º when the beam is pointing horizontally.

"j" is the residual angle error.

TERR-j.WMF

Transit axis tilt, i



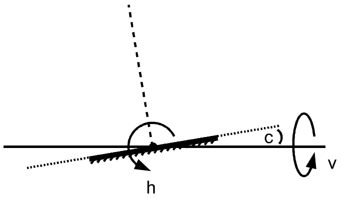
Transit axis tilt: i

The transit axis should be perpendicular to the primary (standing) axis.

"i" is the residual tilt error.

TERR-i.WMF

Mirror tilt, c



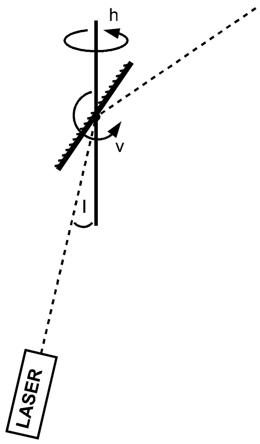
Mirror tilt: c

The plane of the mirror should be parallel to the transit axis.

"c" is the residual tilt error.

TERR-c.WMF

Beam tilt, Ix and Iy



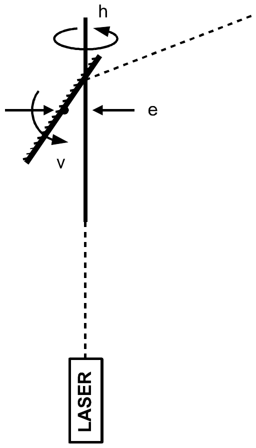
Beam tilt: Ix,Iy

The laser beam should be parallel to the primary (standing) axis.

"Ix,Iy" are the residual tilt components.

TERR-Ixy.WMF

Transit axis offset, e



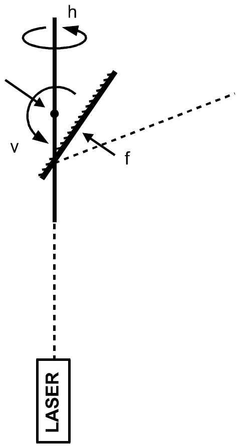
Transit axis offset: e

The transit axis should intersect the primary (standing) axis.

"e" is the residual offset error between the axes.

TERR-e.WMF

Mirror offset, f



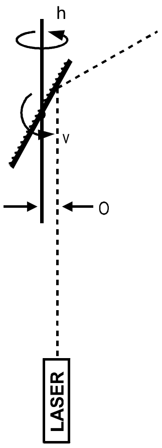
Mirror offset: f

The plane of the mirror should be on the rotation centre where the axes intersect.

"f" is the residual offset error.

TERR-f.WMF

Beam offset, Ox and Oy



Beam offset: Ox,Oy

The laser beam should lie exactly on the primary (standing) axis.

"Ox,Oy" are the components of the residual offset error.

TERR-O.WMF

Note

Use of the collar reflector ensures that these parameters are always zero and they are not normally used in the error model.

Cover plate offset, O2x and O2y

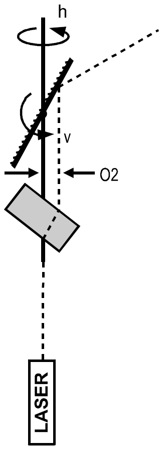


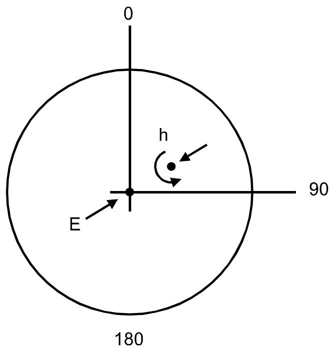
Plate offset: O2x,O2y

Refraction at the cover plate may move the laser beam off the primary (standing) axis.

"O2x,O2y" are the components of the residual offset error.

TERR-O2.WMF

Horizontal encoder eccentricity, Ex and Ey



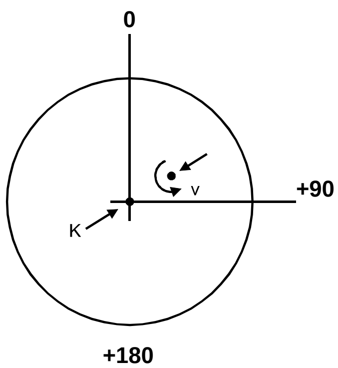
Horizontal encoder eccentricity: Ex,Ey

The encoder centre and its rotation centre should be the same point.

"Ex,Ey" are the components of the error.

TERR-Exy.WMF

Vertical encoder eccentricity, Kx and Ky



Vertical encoder eccentricity: Kx,Ky

The encoder centre and its rotation centre should be the same point.

"Kx,Ky" are the components of the error.

TERR-Kxy.WMF

Tracker alignment techniques

For introductory information see:
tracker
tracker alignment
tracker alignment parameters

The laser tracker achieves optimal accuracy by using an accurate physical model of the instrument based on 15 tracker alignment parameters, an accurate calculation of *Birdbath distance* and an accurate datum calculation for the *Absolute Distance Meter (ADM).*

Several **tracker alignment techniques** are available to achieve these aims.

Full alignment enables calculation of all 15 tracker model parameters by making sets of *2-face measurements* and *Ball Bar* measurements.

Intermediate alignment enables 3 of the 15 parameters to be calculated in a faster procedure which is therefore ideal for implementing an intermediate update of the model within a general maintenance programme. This method requires only 2-face measurements.

The **2-point test (two point test)** is a technique for determining Birdbath distance. Two fixed and unknown target points are measured from two tracker positions, one on the extrapolated line between the points and one on line between the points. The first measurement establishes the point separation, the second enables calculation of the distance.

The **scale bar test** for Birdbath distance is conceptually similar to 2-point alignment except that the target point separation is defined by the end points on a scale bar. Only one measurement of the end points is required but the technique is not so accurate.

The **ADM offset calculation** finds a datum offset and scale factor which, when applied to ADM measurements, make them compatible with IFM measurements.

The **ADM reflector constant** finds distance offset corrections (reflector constants) which must be applied when using the ADM with *prism retro-reflectors*.

Transformation

A transformation is a general term implying a mathematical conversion between one state and another. For example, raw tracker measurements can be transformed by suitably applied calibration or alignment parameters into corrected values.

In ***Axyz*** the term frequently implies a particular type of transformation, i.e. one which enables 3D data known in one coordinate system to be viewed in another coordinate system.

Coordinate transformations can be calculated in different ways. The function in the ***Axyz*** core module is a particular type of transformation which calculates a best fit between a small number of points whose coordinate values are known in both systems. The computed transformation parameters effectively define a new coordinate system.

For more details see *3D transformation*.

For an alternative technique see *Axis alignment*.

Transit

1) Relating to telescope and mirror movement
When a telescope or mirror is transited it is rotated about the instrument's *transit axis* to point in the opposite direction.

Alternatives:
reversal (of telescope/mirror)

2) Optical tooling
An instrument similar to a theodolite in which an alignment telescope can be rotated about 2 perpendicular axes. In contrast to a theodolite it has 4 footscrews instead of 3 and does not have encoders for measuring the angles of rotation of the telescope.

Translate

In geometry and mechanics, "translate" means to move or shift an object in a particular direction without any rotation.

Triangulation

Diagram: Simple theodolite triangulation
A technique by which targets are located in a global measurement system by measurement of direction from 2 or more fixed and known locations. The method involves angle measurement only.

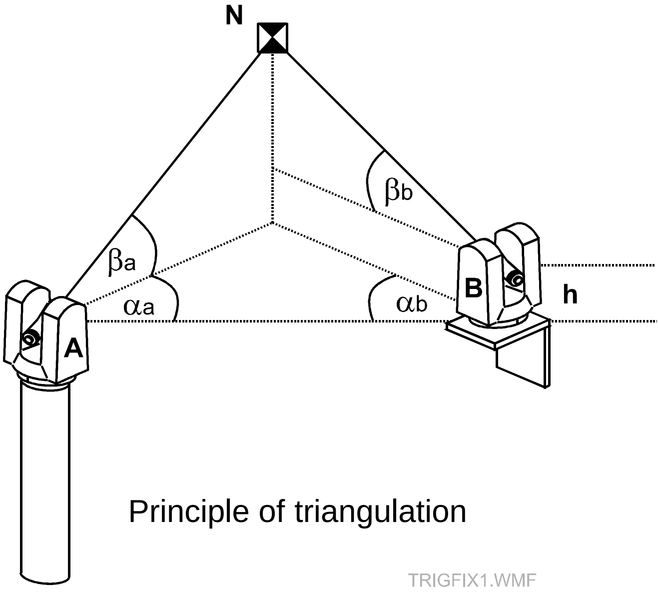
Measurement from one fixed location only places a target on a line in space, hence the need for at least one more direction from a different location to fix a target's position.

In large scale metrology, triangulation is typically implemented by a **theodolite system** or a **photogrammetric system**.

A theodolite system uses two or more *theodolites* to determine angle pointings to a target.

A photogrammetric system uses two or more *cameras* and the methods of *photogrammetry* to determine directions from the imaged positions of targets.

Diagram: Simple theodolite triangulation



Trilateration

A technique by which a target point is located in a global measurement system by distance measurement only. If the distance to a target from 3 fixed, known locations is measured, then the target's location is at the intersection of 3 spheres centred on the fixed points with radii equal to the corresponding measured distances.

Tripod

Photo: Industrial tripod

A device with 3 adjustable legs and possibly an adjustable head, used to support an instrument such as a *theodolite* at a suitable height and location.

Photo: Industrial tripod

U

Unit weighting

A weighting scheme in which all measured items being processed, such as the points to which a surface is fitted, are treated equally and given the same *weight*. For convenience the value of the weight is arbitrarily made equal to unity.

Alternatives:
Uniform weighting

UV

Short for ultraviolet *light*.

V

Variance

Variance is a value which indicates the spread or **dispersion** of *random errors* associated with a measurement. If the spread is small the measurement quality is high. If the spread is large, the measurement quality is low.

The variance is a parameter of the curve which shows the *normal distribution* of the errors. Since errors average out to zero an average value is not a useful parameter since it does not indicate the spread.

Instead the average of the squared error values is used and this is the variance, i.e. for error values e_1 .. e_N the variance (var) is given by:

$$\mathrm{var} = \sum_{i=1}^{N} \frac{(e_i)^2}{N} \qquad \text{or} \qquad \mathrm{var} = \frac{(e_1)^2 + (e_2)^2 + .. + (e_N)^2}{N}$$

Since the variance involves squared values it is not an easily recognized number. A more useful figure is its positive square root, called the **standard deviation** and commonly identified by the Greek symbol σ (sigma):

$$\sigma = \sqrt{\mathrm{var}} \qquad \text{or} \qquad \sigma = \sqrt{\frac{(e_1)^2 + (e_2)^2 + .. + (e_N)^2}{N}}$$

Variance factor

A dimensionless scaling factor for weights in a least squares solution. It should have the value 1.0 if the weighting scheme is correct and there is good redundancy.

Alternatives:
reference variance
variance of a measurement of unit weight
unit variance

Vertex

1) The tip of a cone.

Alternatives:
apex

See also *apex angle*.

2) The point of symmetry on a paraboloid where the axis intersects the surface.

Vertical angle

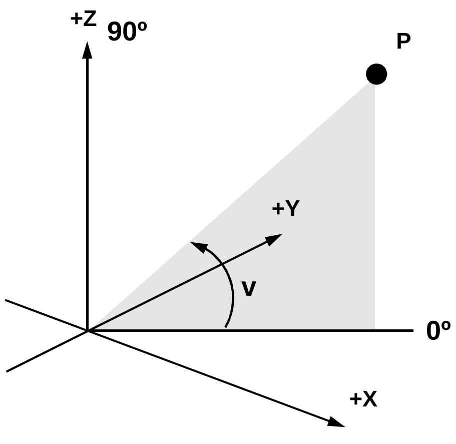
Diagram: Vertical angle
An angle measured from a horizontal plane to a target point of interest. The angle is positive if the point is above the plane and negative if below.

A vertical angle of 0° means that the target point is at the same height as the measuring instrument.

The angle is measured on the **vertical circle** of a theodolite, Total Station or laser tracker. The term is commonly used even if the instrument is only approximately levelled.

The term is sometimes loosely used when referring to the *zenith angle*. However a zenith angle has a different datum point and the terms must be used carefully to avoid ambiguity.

Diagram: Vertical angle



Vertical angle, v

ANGL-VER.WMF

VSTARS

Short for Video Stereo Triangulation And Resection System.

Name of a commercial video triangulation system built by Geodetic Services Inc., Florida, USA (GSI) and sold by GSI and Leica.

W

Weight

A value given to a measurement or coordinate which reflects its relative quality compared with other measurements or coordinates. A high weight implies high quality.

If quantities to be weighted are considered to be equally good they will all typically be assigned a weight value = 1.

If quantities to be weighted have variable quality, weight values will typically be based on *weighting by standard deviation*.

Sometimes weighting is applied to points where one or more of the 3 coordinate values is unknown. For example, *control points* may only be known in plan or height. These are known as **partially weighted** points in contrast to **fully weighted** points where all 3 coordinate values are known.

Weighting by standard deviation

A weighting scheme in which all measured items being processed, such as the points to which a surface is fitted, are given a *weight* which depends on their estimated **standard deviation** (σ). The value of the weight actually depends on the square of the standard deviation, known as the *variance* and is calculated as follows:

$$\text{weight} = \frac{\text{const}}{\sigma^2}$$

The constant value is arbitrary and is normally given a value equal to unity. From this it can be seen that an item with a large standard deviation has a low weight, implying low quality and one with a small standard deviation has a high weight, implying high quality.

Alternatives:
Weighting by variance

Wild

Wild Heerbrugg was a Swiss manufacturer of equipment for map-making and industrial measurement. Founded in 1921 by Heinrich Wild and Jakob Schmidheiny it has been part of Leica since 1990.

The site in Heerbrugg, eastern Switzerland, is still the main manufacturing site for map-making and industrial equipment within Leica. Wild instruments are still in use in many industrial measurement systems.

The German pronunciation of Wild is like "Vilt".

Workpiece

To provide a flexible level of organization which accommodates many arrangements of *objects*, ***Axyz*** introduces a fundamental component of an object called a workpiece. This could be regarded as a physical component such as a car door or a more abstract "container" where a certain class of points are stored. All measured objects therefore become collections of one or more workpieces.

To preserve the integrity of the job file, every new job is provided with one workpiece called the **default workpiece** and which has the name "default". Unlike workpieces created by the user, this cannot be renamed or deleted.

At any time one of the defined workpieces is the **active workpiece**. This is the default workpiece for storing data. Users do not therefore explicitly have to use this name when assigning IDs to new items of data. The active workpiece can be re-defined at any time and may be overridden by explicit use of a different workpiece name.

Z

Zenith

A position vertically above the measuring location.
A direction which points vertically up.

Zenith angle

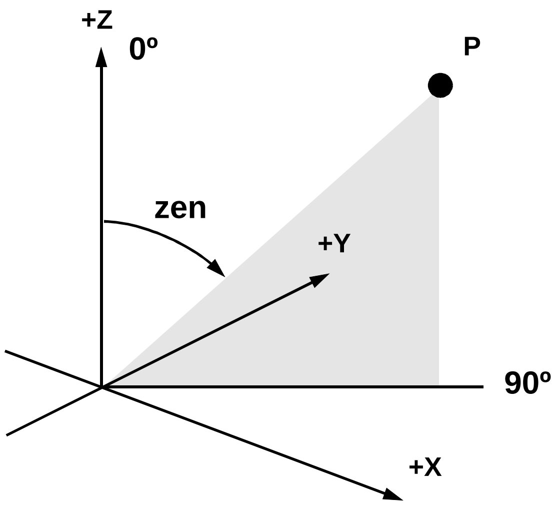
Diagram: Zenith angle
An angle measured from the *zenith* to the target point of interest.

A zenith angle of 90° means that the target point is at the same height as the measuring instrument.

The angle is measured on the **vertical circle** of a theodolite, Total Station or laser tracker. The term is commonly used even if the instrument is only approximately levelled.

The zenith angle is sometimes loosely called the *vertical angle*. However a vertical angle has a different datum point and the terms must be used carefully to avoid ambiguity.

Diagram: Zenith angle



Zenith angle, zen

ANGL-ZEN.WMF

Index

U

V

W

Y