



INSTRUMENT CALIBRATION

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INSTRUMENT CALIBRATION

✿ Why?

- ✿ **All measurements ultimately traceable to National Standards**
- ✿ **Guarantee of measurement quality**
- ✿ **Foundation for later work with derived quantities**

INSTRUMENT CALIBRATION

✱ **Why?**

✱ **Anyone can make a measurement, but...**

Measurement experts produce the best measurements...

Or else they aren't measurement experts!

INSTRUMENT CALIBRATION

* Why?

* **The main (only?) reason surveys are done is to support decision-making**

* **Good measurements —>
Good decision support products —>
Good decisions**

INSTRUMENT CALIBRATION

✱ Why?

✱ **Good professional practice**

✱ **Builds professional credibility**

✱ **Quantifies errors and uncertainties in measurement**

✱ **Integration of new technologies**

INSTRUMENT CALIBRATION

*** How?**

*** Varies with different instruments**

*** Some calibrations can be done by anyone**

*** Some need support equipment**

*** Some need a calibration laboratory**

NATIONAL STANDARDS

- ✦ **Solve the problem of ‘infinite regress’**
- ✦ **Keep all measurements consistent**
- ✦ **Keep measurements independent of other considerations**
- ✦ **One nation: one standard**

LEVELING

- ✱ **Levels can be checked independently**
- ✱ **Collimation error, compensator errors and closure capabilities can be checked easily**
- ✱ **Problem Areas:**
 - ✱ **Calibration of rods, especially bar-code rods**
 - ✱ **Stability of marks**
 - ✱ **Temperature of rods**

ANGLE MEASUREMENT

- ❖ **Traditional angle-measuring equipment can usually be checked independently**
- ❖ **Errors and inconsistencies, if found, cannot be easily corrected outside a repair facility**
- ❖ **In most cases, proper reading procedures (International Standards) will isolate errors**

DISTANCE MEASUREMENT

- * Calibrating tapes is fairly straightforward, if rarely done these days**
- * EDM calibration is a big topic, which will form the bulk of this presentation**
- * Ultimately, EDM calibration cannot be done independently of the National Standards**

GPS

- ❖ **Antenna calibration is the main concern**
 - ❖ **This can be done independently, but is not always easy**
- ❖ **Overall GPS performance variability tends to be more of a concern than individual instrument variability**
- ❖ **Calibration of entire system's performance is more critical, but can be done independently**

LASER SCANNERS

- ✿ **Calibration for both angular and distance measurement is required**
- ✿ **Requires a field of known points across a full hemisphere**
- ✿ **Software for forming surfaces from point clouds must be part of the calibration process, as it is part of the measurement process**

TERRESTRIAL CAMERAS

- ✱ **Cameras can be calibrated independently if a suitable range is set up**
- ✱ **Consistency in camera calibration is more important than an individual calibration, with most modern digital cameras**
- ✱ **Development of self-calibration with each frame will help improve measurement quality**

AERIAL CAMERAS

- ✱ **Can be calibrated by suitable ground arrays and in-flight calibration**
- ✱ **Self-calibration through aerotriangulation provides high levels of measurement precision and reliability**
- ✱ **Laboratory calibration is always possible**

LIDAR

- ✱ **Can be calibrated with known ground points, in a similar manner to in-flight calibration in aerial cameras**
- ✱ **Current research problems include the equivalent of aerotriangulation, trying to tie together LIDAR strips**
- ✱ **This ties back to GPS and INS calibration**

AERIAL SCANNERS

- ✱ **More difficult to calibrate, as pushbroom scanners have the equivalent of a 'principal line' rather than the 'principal point' of camera imagery**
- ✱ **Calibration of GPS and INS control instruments for the scanners is a critical issue**
- ✱ **Ground control only works in the immediate area**

SAR

- ❖ **Synthetic Aperture Radar (SAR) is exceedingly difficult to calibrate, as the ‘measurements’ are highly correlated through the signal processing**
- ❖ **The location information acquired is self-consistent, but very difficult to connect to other location information**

SUMMARY OF INSTRUMENTS

- ✿ **The following can be calibrated fairly easily:**
 - ✿ **Levels**
 - ✿ **Angle-measuring equipment**
 - ✿ **Cameras (with one proviso *)**
- ✿ **They do not require major calibration investments and can be done by almost anyone**

SUMMARY OF INSTRUMENTS

- ✱ **The following can be calibrated with a suitable test range:**
 - ✱ **Laser scanners**
 - ✱ **Cameras**
 - ✱ **GPS**
- ✱ **The test range can be fairly simple, but does require some calibration ***

SUMMARY OF INSTRUMENTS

- * The following require major calibration of the entire measurement system, especially GPS and INS components:**
- * LIDAR**
- * Aerial scanners**
- * These are complex systems with highly correlated outputs**

SUMMARY OF INSTRUMENTS

- ❖ **SAR calibration, beyond internal applications, is still a major research area**
- ❖ **Distance measurement, as well as leveling rod calibration, cannot be done without connection to the National distance standards**
- ❖ **This connection for distance measurement provides a foundation for calibrating laser scanners, cameras and GPS**

BY-THE-WAY NOTE...

- ❖ **The greater the complexity of a measurement system, the more difficult it is to calibrate it**
- ❖ **Highly correlated measurements mean highly complex calibration procedures, or laboratory calibration of fundamental components**
- ❖ **Measurement systems must be calibrated as a single entity**

DISTANCE MEASUREMENT

- * Distance measurement, today primarily EDM, has a pivotal role in calibration generally**
- * Calibrated EDM brings the connection to National distance standards that some of the other technologies require for their calibration, e.g., cameras and laser scanners**
- * Calibrating EDM is therefore critical**

EDM CALIBRATION

- ✱ **NGS used to provide EDM calibration service**
- ✱ **Calibrated base lines, re-calibrated, with available data**
- ✱ **This ended in the early 1990s, because some NGS people believed that EDM would disappear and be replaced by GPS**

EDM CALIBRATION

- ✿ **EDM calibrated base lines (CBLs) in the US use the 'Aarau' design, but:**
- ✿ **Distances used are not always correct for the Aarau design**
- ✿ **No cyclic error measuring range is provided**
- ✿ **Design is based on instruments in use 30+ years ago, and so not suited to current gear**

EDM CALIBRATION

- ✱ **CBLs are re-calibrated as opportunity and funds are available**
- ✱ **This depends very much on having an active NGS state representative!**
- ✱ **Some Minnesota CBLs were calibrated in 2002**
- ✱ **ND, SD, NE, IA, WI, IL: 1 CBL post-1993 (new)**
- ✱ **IN: 1 CBL in state, now destroyed**

EDM CALIBRATION

- ✱ **NGS calibrates CBLs using a pair of Wild DI-2002 EDM (1 mm + 1 ppm), which was manufactured 1989 to 2001**
- ✱ **NGS uses a thermistor array and barometers to determine atmospheric corrections**
- ✱ **NGS uses a high precision plummet for centering over ground marks, and a single calibrated prism**

EDM CALIBRATION

- ❖ **Users don't always calibrate their optical plummets, and so introduce centering errors**
- ❖ **Users don't calibrate thermometers and barometers, if they use them**
- ❖ **Users don't calibrate individual prisms**
- ❖ **Calibrating an EDM unit takes several hours**
- ❖ **Users don't always understand how to compare their measurements to the CBL**

EDM CALIBRATION

- ✱ **Old CBLs have uncertain stability, which leads to uncertainty in scale error determination**
- ✱ **CBL design that is incompatible with current EDM, together with lack of prism calibration, leads to uncertainty in zero error determination**
- ✱ **CBLs cannot determine cyclic error**
- ✱ **In summary, current CBLs cannot guarantee any part of EDM calibration**

NGS POLICY

- ✿ **NGS is aware of these problems, but budget constraints limit their action**
- ✿ **NGS plan to build a modern CBL at Corbin, VA within a year or two**
- ✿ **NGS uncertain about national EDM calibration policy, largely because of cost and user indifference**

AND OVERSEAS...

- ❖ **Australia (and NZ): each state has at least 5 CBLs of modern design, re-calibrated annually with a Mekometer or Geomensor (0.1 mm + 0.2 ppm), plus user instructions and software for calibration downloadable**
- ❖ **Finland: CBLs calibrated to better than 0.1 mm for over 50 years**
- ❖ **Canada: Modern CBLs and Mekometer use**

ERRORS IN EDM

- ✱ **Once systematic errors (such as meteorological errors) and gross errors (such as centering errors) are eliminated, there are three main errors left:**
- ✱ **Zero or offset error**
- ✱ **Scale error**
- ✱ **Cyclic error**
- ✱ **Small errors remain, such as short-range, range-dependent and time-of-operation errors**

ERRORS IN EDM

- ❖ **Regular calibration, as on a CBL, attempts to quantify the three main errors**
- ❖ **The baseline design attempts to achieve the calibration with the minimum of time and effort by the users**
- ❖ **The small errors require more specialized baselines and procedures to determine**

EDM ERRORS

- ❖ **Zero or offset error is caused by a difference between where the EDM measures its zero point, and the location of the ground mark**
- ❖ **The reflector offset is included in this error, as the reflector is part of the whole measurement system**
- ❖ **This error is usually constant for all measurements**

EDM ERRORS

- ✱ **Scale error is caused by differences in the oscillator frequencies, which change the length of the fundamental distance unit**
- ✱ **All distances are incorrect by a consistent factor, in the same way that applying the wrong PPM correction affects measurements**
- ✱ **Cannot be determined without a CBL**
- ✱ **Variable scale error is usually terminal**

EDM ERRORS

- ✱ **Cyclic error is caused by variation in measuring the phase differences used to determine the fine line lengths**
- ✱ **It appears as a sine wave difference between calibrated distances and measurements, with the period equal to the EDM fundamental distance**
- ✱ **Needs to be measured across the entire EDM fundamental distance**

EDM CALIBRATION

- ✱ **In its simplest form, if I measure the distance between two points (N and S) with an EDM, the measured distance will be:**

$$\text{Measurement NS} = D + \varepsilon$$

- ✱ **The D is the 'true' distance and ε is the zero or offset error**
- ✱ **If I now measure the distance in two parts...**

EDM CALIBRATION



✱ **Measurement MN = $d_1 + \epsilon$**

✱ **Measurement MS = $d_2 + \epsilon$**

✱ **Now $D = d_1 + d_2$**

✱ **$MN + MS = d_1 + \epsilon + d_2 + \epsilon = d_1 + d_2 + 2\epsilon$**

✱ **$MN + MS - NS = d_1 + d_2 + 2\epsilon - (d_1 + d_2 + \epsilon) = \epsilon$**

EDM CALIBRATION

- ✱ **To find the cyclic error, measure the distance to a prism at multiple points along a rail or wall, over the EDM fundamental distance**
- ✱ **Zero/offset error and scale error should remain constant for this exercise**
- ✱ **Plot the difference between the EDM distance and the 'known' distance for each measurement, forming the cyclic error plot**

EDM CALIBRATION

- ❖ **To find the scale error, first find and eliminate the zero or offset error, together with the cyclic error, from all measured distances**
- ❖ **Compare the resulting distances with calibrated distances**
- ❖ **Any consistent scale difference (as a scale factor) is the scale error**

EDM CALIBRATION

- ✱ **It should be possible to combine these different procedures into a single procedure**
- ✱ **If we know the various distances within the CBL (from the calibration) we should be able to solve for all the calibration corrections at once, using Least Squares Adjustment**
- ✱ **This is the ideal situation**

FUNDAMENTAL DISTANCES

- ✿ EDM fundamental distances are those used for fine measurements by phase difference
- ✿ While many instruments used 10m (almost no instruments ever used feet), this is less common, as the fundamental distances shrink
- ✿ 1.5, 2, 3, 3.333, 5, 7.5, 10, 10.101, 20, 30.769 and 33.333 m have been used

CBL DESIGNS

- ✿ **There are three basic designs:**
 - ✿ **Aarau**
 - ✿ **Heerbrugg or Schwendener**
 - ✿ **Hobart or Sprent/Zwart**
- ✿ **The Aarau design is considered obsolete, but its design approach is instructive**

AARAU DESIGN

- ✱ **Named for the Swiss city where Kern was based**
- ✱ **Developed in the 1960s**
- ✱ **Two components, a long main line and a short cyclic error range**
- ✱ **The long line has marks at multiples of the EDM fundamental distance unit (10m back then)**
- ✱ **The short range measures finely over 10m only**

AARAU DESIGN

- ✱ **By making the main line in multiples of the EDM fundamental distance unit, cyclic error is constant for all measurements**
- ✱ **The main line is used to determine scale and offset error, by measuring all component lines**
- ✱ **The 10m range is used to determine the cyclic error, which is then applied to the main line data to finalize the calibration**

AARAU DESIGN

- ✱ **One problem is that not all instruments have a 10m fundamental distance**
- ✱ **More instruments can be accommodated if the long line has points at multiples of 60m, as shown**
- ✱ **The need for the short range, usually based on a rail with stops, adds to cost and time factors**



HEERBRUGG DESIGN

- ❖ **Originally presented by Schwendener, who then (1972) worked for Wild in the Swiss city of Heerbrugg**
- ❖ **The distances are spread so that their remainders collectively cover the fundamental unit distance (original design was for 10m)**
- ❖ **All line components are measured**

HEERBRUGG DESIGN

- ✱ **This is probably the most comprehensive design, and it can be modified to allow use of almost all EDM fundamental distance lengths**
- ✱ **This is the design recommended for the new NGS baseline to be built in Corbin, VA**
- ✱ **Has more points and so components**



HOBART DESIGN

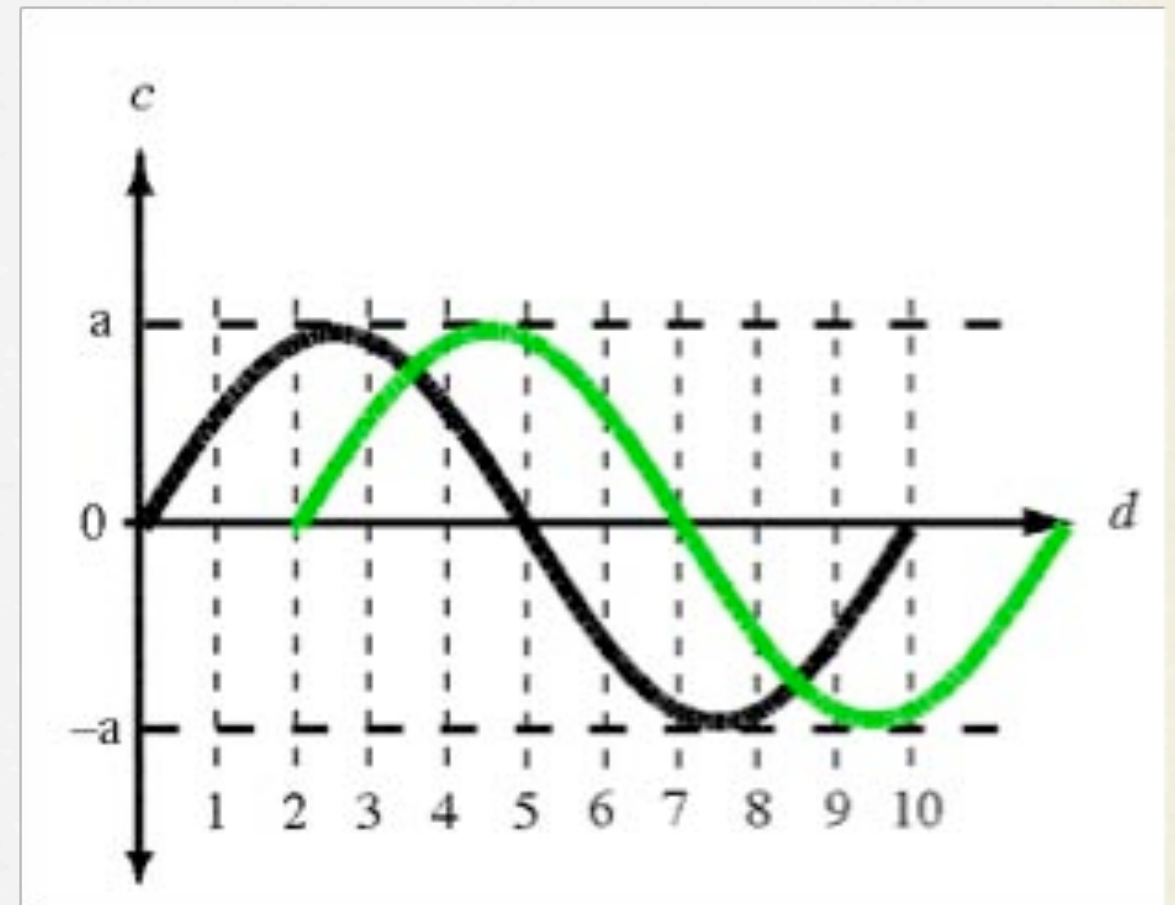
- ❖ **Developed by Sprent and Zwart, then at the University of Tasmania, Hobart, Australia, in 1978**
- ❖ **The design is an effort to simplify the Heerbrugg design, in terms of practical use, and is based on 10m EDM fundamental distances**
- ❖ **The objective is to limit instrument set-ups to just two, albeit with multiple measurements each**

HOBART DESIGN

- ✱ **The two instrument points are 5m apart (half the EDM fundamental distance)**
- ✱ **The other points are set up to have their remainders spread across the EDM fundamental distance, but so that there are matched pairs**
- ✱ **Measurements from the two set-up points cancel out the cyclic error for zero/offset and scale error determination**

HOBART DESIGN

- ✿ **Once the zero/offset and scale errors are determined, the cyclic error is recovered from the various measurements**



MODERN DESIGN

- ✱ **Modern CBLs use pillars to provide:**
 - ✱ **High stability**
 - ✱ **Consistent and short EDM heights**
 - ✱ **No set-up centering errors**
 - ✱ **A more definite measurement procedure**
 - ✱ **Faster instrument set-up**

MODERN DESIGN

- ✱ **Modern CBLs use a curved design, so that prisms can be set up on all the pillars at once**
- ✱ **All distances can be measured from each instrument point without having to move or cover reflectors**
- ✱ **Avoids possible signal interference**
- ✱ **Greatly speeds operations**

MODERN DESIGN

- ✱ **Modern CBLs are regularly calibrated by high-precision EDM, e.g., Mekometer**
- ✱ **User calibration software is based on Least Squares Adjustment and solves for all parameters**
- ✱ **The software guides the user through the calibration process, in the field**
- ✱ **Calibration procedures are streamlined to be quick and efficient**

MODERN DESIGN

- ✿ **Updated calibration parameters for each CBL can be downloaded as soon as they are made available, and the software uses the latest values**
- ✿ **Calibration provides a legal trail back to the National distance standards**
- ✿ **Ease of use means that equipment can be calibrated more frequently, e.g., annually**

CBL RESEARCH

- ✿ **Almost no research and development on this issue in the US, ever!**
- ✿ **Main research work in Finland and Australia (University of NSW), although Jan Rüeger is now nominally retired**
- ✿ **RICS (UK) recently released a book on EDM calibration, as well as a Guide Note**

CBL RESEARCH

- ❖ **The new NGS CBL design was developed by SCSU professor (actually 4 designs submitted)**
- ❖ **SCSU Land Surveying intend to develop a new collaborative center for measurement calibration research, development and dissemination**
- ❖ **Focus will be on calibration of as many measurement technologies as possible, but EDM has the highest priority**

THE FUTURE...

- ✿ **Conventional EDM will be calibrated by modern CBLs across the country**
- ✿ **This will form the backbone of the larger calibration effort**
- ✿ **New technologies will have calibration methods developed, so users can have definite and defined confidence in their measurement data (at least)**

THE FUTURE...

- ❖ **As spatial measurement technologies become ubiquitous and largely invisible, surveyors will remain the spatial measurement experts**
- ❖ **Surveyors' expertise should extend from spatial measurement right around the spatial information cycle, but the connection to the fundamentals of measurement must not be lost**



**THANK YOU FOR YOUR
ATTENTION!**