



IWAA97
Argonne National Laboratory

Considerations in the Measurement of Particle Accelerators with Laser Trackers

Bob Bridges
SMX Corporation



Topics

- Tracker Measurement, Certification, and Characterization
- Radial Measurement
- Transverse Measurement
- Level Measurement
- Accelerator Applications



Tracker Measurement

Coordinates

- Radial distance
 - Interferometer or absolute distance (ADM) system
- Azimuth angle and elevation angle
 - Angular encoders

Other

- Level
- External temperature sensors



Tracker Certification

Performance Tests

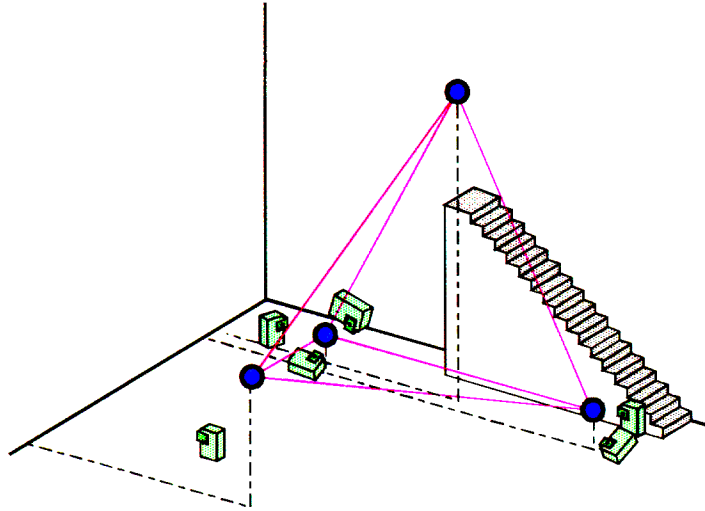
- Calibration: Confers traceability in either the *strong* or *weak* sense
- Compensation
- Interim Tests

Standards

- ANSI standard: *ASME Working Group B89.4.19*
- ISO standard



Tetrahedron Artifact



Tracker Characterization

- **ISO Reference Documents:** The *GUM* and the *VIM*
- **Accuracy:** The difference between the true value and the measured value
- **Repeatability:** The “spread” of values measured under fixed conditions and over a short time. Varies as $1/\sqrt{N}$
- **Uncertainty:** An estimate of the “dispersion” of values reasonably attributed to the measurand



New Type of Radial Measurement: ADM

- **Radial Measurement Technologies**
 - Interferometer: Fringe counting with a HeNe laser
 - Absolute distance (ADM) system: Pulse and sinusoid time-of-flight with a semiconductor laser
- **Purpose of ADM**
 - Interferometer loses count if the beam is broken
 - ADM sets distance and passes to interferometer
- **Applications of ADM**
 - Multiple targets; cluttered environments



Radial Uncertainty

Interferometer

- Distance formula $r = N\lambda_0/2n_A$
- Uncertainty
 - In fringe count $\Delta N/N \sim 10^{-7}$
 - In vacuum wavelength $\Delta\lambda_0/\lambda_0 \sim 10^{-7}$
 - In refractive index of air $\Delta n_A/n_A \sim 10^{-6}$

ADM

- Distance formula $r = N_{RF}\lambda_{0,RF}/2n_{A,G}$
- Uncertainty: similar to above but slightly higher $\Delta N/N$



Refractive Index of Air

- **Calculations:** Edlin or Ciddor equation
- **Sources of uncertainty:** (1) sensor uncertainty, (2) variations in the air
- **Rules-of-thumb for length error**
 - Temperature 1 ppm/°C
 - Pressure 0.4 ppm/mmHg
- **Typical accuracies (1 sigma)**
 - In index: $\Delta n_A/n_A \sim 1$ ppm
 - In length: $\Delta r_{\text{tot}} = \{0.0011, 0.0015\}$ inch @ 115 ft



Other Radial Considerations

- **Periodic Calibration**
 - Weather station sensors (thermometer, barometer)
- **Home Reset**
 - Corrects “dead path” lengths
- **Offset Compensations**
 - Pivot to home (R0), Pivot to back mirror
- **ADM Compensation and Calibration**



Transverse Accuracy

- **Basic Accuracy:** ~ 5 times larger than radial

$$\Delta x_{\text{trans}} = \Delta(r\sqrt{\theta^2 + \phi^2}) \sim 5 \text{ ppm}$$

- **Quadratic Effects**

- Transverse temperature gradient

$$\Delta x_{\text{trans}} \cong (10^{-6} \Delta T / ^\circ\text{C})(dT/dx_{\text{trans}})r^2$$

$$\Delta x_{\text{trans}} \cong 0.5 \text{ mm (@ } dT/dx_{\text{trans}} = 1 ^\circ\text{C/m, } r = 30 \text{ m)}$$

- Pressure gradient $\Delta x_{\text{trans}} = 15 \mu\text{m}$ (at $r = 30 \text{ m}$)

- Earth's curvature $\Delta x_{\text{trans}} = 70 \mu\text{m}$ (at $r = 30 \text{ m}$)

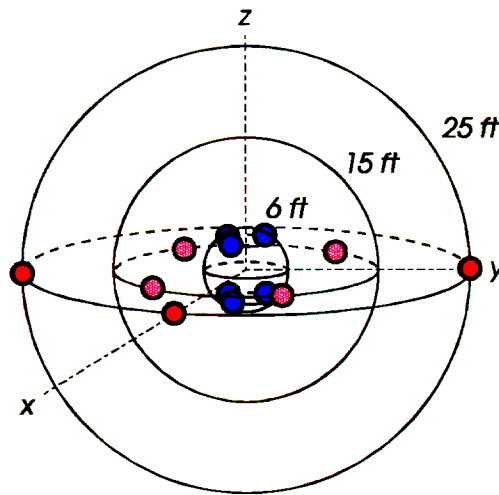


Transverse Compensation

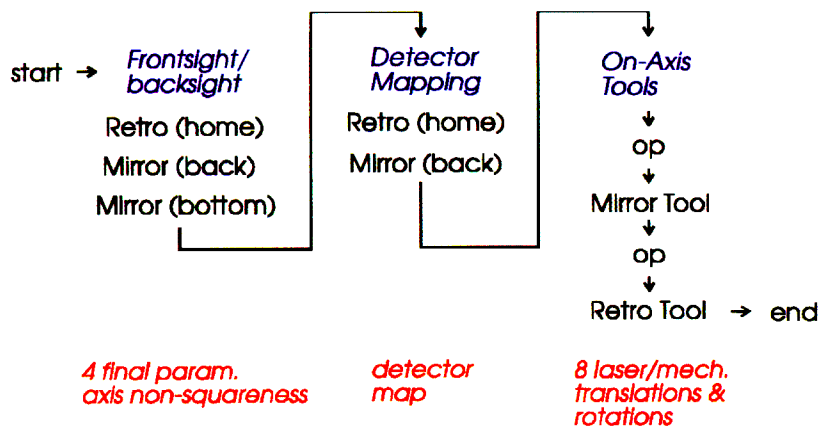
- **Angular Encoders:** Mapping improves accuracy.
- **Laser / Axis Alignment:** Compensation parameters improve accuracy.
 - *Axis* Axis offset and axis non-squareness
 - *Laser offset* Δx and Δy between axes and laser
 - *Laser tilt* θ_x and θ_y between axes and laser
 - *Retrace coordinates*
 - *Encoder corrections*



Traditional Aim Compensation



The Routine AIM Compensation





Level

Technology

- Accelerometer that uses an electromagnet to “balance” a pendulum

Accuracy

- 1 arc second

Application

- Rapidly determine whether accelerator components are properly aligned with respect to gravity
- Improve angular accuracy along the short dimension of the tunnel



Calculation of Measurement Uncertainty

- **Random (Repeatability) Components:** Reduce by $1/\sqrt{N}$
 - Tracker repeatabilities: radial, transverse
 - External repeatabilities: vibration, targets, etc.
- **Systematic (Accuracy) Components:**
 - Tracker accuracies: radial, transverse
 - External errors: thermal gradients, “bumps,” etc.
- **Calculation Procedure:** Start with the appropriate formula; take derivatives and multiply by independent variables; calculate the RSS value.



Installation and Alignment of Accelerator Components

- **Types of Components:** Dipoles, quadrupoles, sextupoles, collimators, etc.
- **Types of Measurements**
 - Coordinates: Component control points and axes
 - Coordinates: Tunnel control points
 - Relative Orientation: Among control points and with respect to gravity
 - Expansion: Temperature sensors compensate for material expansion



Trackers in Accelerator Installation and Alignment

Page 1 of 2

- **Advantages:** Faster and more accurate than theodolites, especially in long, narrow tunnels
- **ADM:** Speeds alignments by enabling rapid measurement of multiple targets. Also useful for tight spaces and cluttered environments.
- **Headset:** Enables single-person alignments. Useful companion accessory for ADM.



Trackers in Accelerator Installation and Alignment

Page 2 of 2

- **Level:** Quickly and accurately determines orientation with respect to gravity.
- **External Temperature Sensors:** Convenient way to compensate for material expansion
- **Take Advantage of Radial Accuracy:** e.g., Put the tracker in line with with the tunnel control points.