IWAA97
Argonne National Laboratory

Considerations in the Measurement of Particle Accelerators with Laser Trackers

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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

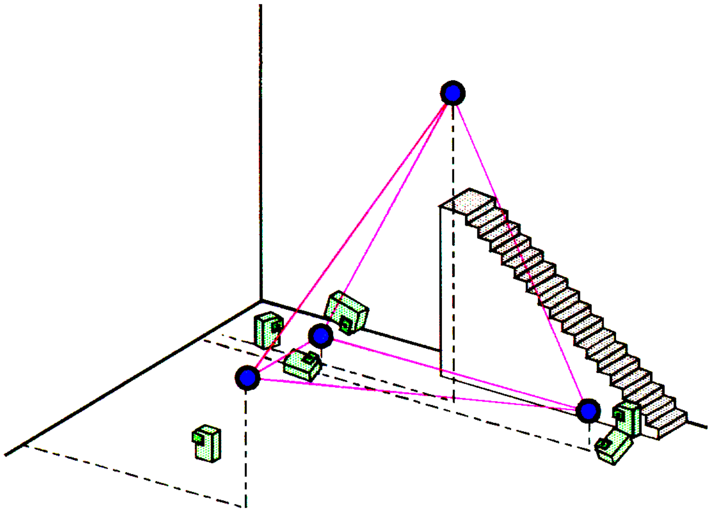
Performance Tests

- 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 $1\ \text{ppm}/{}^\circ\text{C}$
  - Pressure $0.4\ \text{ppm}/\text{mmHg}$
- **Typical accuracies (1 sigma)**
  - In index: $\Delta n_A / n_A \sim 1\ \text{ppm}$
  - In length: $\Delta r_{\text{tot}} = \{0.0011,\ 0.0015\}\ \text{inch @ } 115\ \text{ft}$

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

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

- **Quadratic Effects**
  - Transverse temperature gradient

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

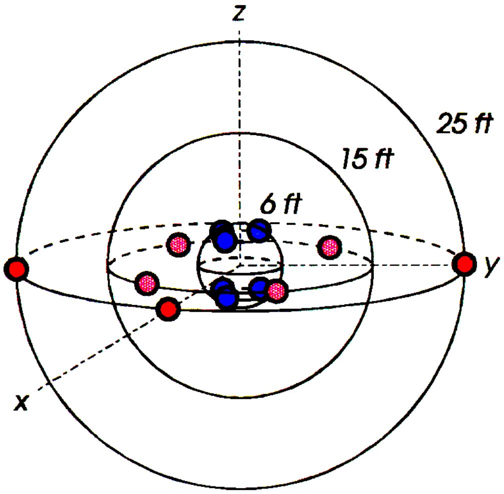
    $$\Delta x_{\text{trans}} \cong 0.5\text{ mm}\ (@\ \ dT/dx_{\text{trans}} = 1\ {}^\circ\text{C/m},\ r = 30\text{ m})$$

  - Pressure gradient $\Delta x_{\text{trans}} = 15\ \mu\text{m}$ (at $r = 30$ m)
  - Earth's curvature $\Delta x_{\text{trans}} = 70\ \mu\text{m}$ (at $r = 30$ m)

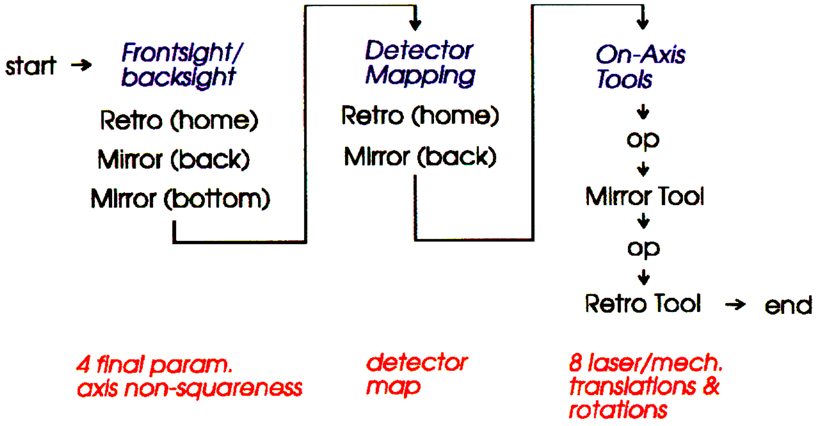
Transverse Compensation

- **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



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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

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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

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Trackers in Accelerator Installation and Alignment

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- **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

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- **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.