A SURVEY OF ACCELERATOR ALIGNMENT CONCEPTS FOR PROFESSIONAL DEVELOPMENT*

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Abstract

Research laboratory engineering departments encourage employees to pursue professional development in their field. Within the accelerator alignment community, limited introductory resources address the unique considerations of this specialized discipline. This paper aims to cover important alignment concepts in an engaging and exploratory manner utilizing a multiple-choice quiz format to help newer alignment engineers review key professional concepts. The desired outcome is for group leaders to use the concepts presented here to aid in the professional development of newer members. The included answer key and brief explanations after each question are designed to inspire further learning and research of the topics. Topics covered include network survey planning, geometric impacts on measurement accuracy, fiducialization techniques, and alignment smoothing.

QUESTIONS

Question 1

A laser tracker is located into a working coordinate system by observing survey network monuments grouted in the floor with known coordinates (M1 through M5). The known coordinates of M1 through M5 are equally well established from a recent survey campaign. Next, the laser tracker is used to measure the location of 3 new points on the floor (P1, P2, P3). The coordinates of P1, P2, and P3 are then recorded after they are measured.

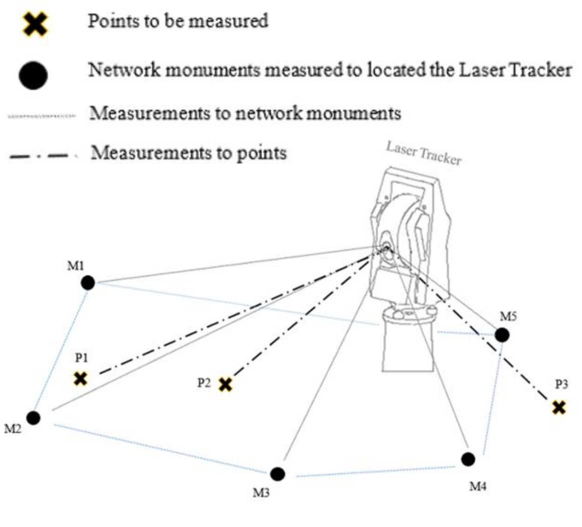

Figure 1: Survey Geometry for Question #1

Given the geometry of where the laser tracker, monuments, and points are (shown in Figure 1), which choice correctly ranks the accuracy of the observed coordinates for P1, P2, and P3 from MOST accurate to LEAST accurate?

A) P1, P2, P3 **B)** P2, P1, P3
C) P2, P3, P1 **D)** P3, P2, P1

Question 2

What hardware-related questions should be considered during the design and prototype testing of a component's alignment adjuster system? Select all that apply.

A) Is there enough space for personnel to access the adjusters?
B) Is a reasonable amount of torque sufficient to move components smoothly?
C) Are there sufficient degrees of freedom of motion for the alignment process to converge?
D) Is the component fiducialized?
E) Is there sufficient stiffness and stability to lock components in place once aligned?
F) Are any surfaces that slide across one another either made from dissimilar materials or lubricated?

Question 3

Seven points were measured on a planar surface and a plane was fit to the measurements (shown in Figure 2). Cones are plotted to show the deviations (in mm) from the measured points to the least-squares best-fit plane (positive deviations are above the plane, negative are below the plane). The deviations are the following: +3.0 mm, +0.7 mm, +0.3 mm, -0.2 mm, -0.7 mm, -0.8 mm, -2.3 mm. What is the flatness and RMS (Root Mean Squared error) of the plane based on these measurements?

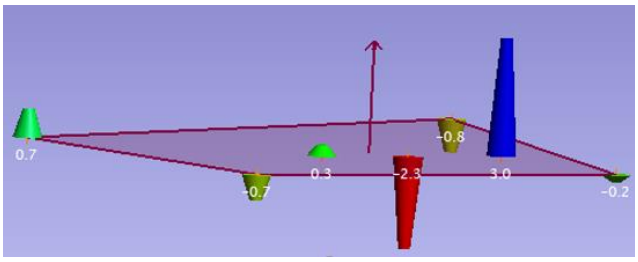

Figure 2: Plane Inspection Measurements for Question 3

A) Flatness = 3.0 mm; RMS = 1.5 mm
B) Flatness = 5.3 mm; RMS = 1.1 mm
C) Flatness = 5.3 mm; RMS = 1.5 mm
D) Flatness = 3.0 mm; RMS = 1.1 mm

Question 4

A digital level is used to measure height differences between two floor monuments. Why is it a best practice to place the digital level halfway between the two points?

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A) So that people can see which two points are being measured.
B) So that the backsight readings will equal the foresight readings.
C) So that any systematic errors in the backsights and foresights will be equal but opposite in sign and cancel each other out when calculating height differences.
D) So that blunders can be more easily identified in a network adjustment statistical analysis.

Question 5

It is suspected that a digital level's line of sight is not truly level. What test should be done to test this?

A) A two-peg test
B) A straightness of sighting test
C) A parallax test
D) An altimeter test

Question 6

A component needs to be fiducialized by probing mechanical features with a portable CMM as shown in Figure 3. A central axis is defined by connecting two measured circle centers—one measured at the upstream end and one at the downstream end. The component's top-plane is also measured. The central axis of the component is desired to be placed on a horizontal beamline to define the component's yaw and pitch orientation. The top-plane's normal vector is desired to be pointing up to define the component's roll. The measured angle between the top-plane normal vector and the central axis is 90.02 degrees. Using the fiducialization data, how should the ideal placement be determined?

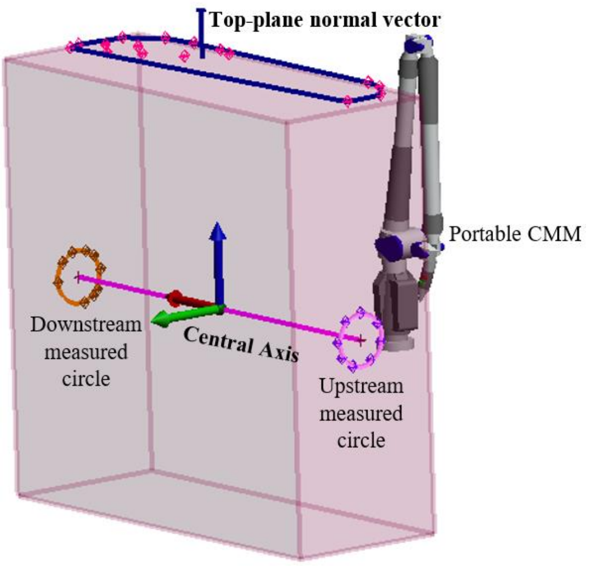

Figure 3: Magnet Fiducialization Measurements

A) The top-plane's normal vector should be held as the primary axis, and the central axis should be the secondary axis. The third axis follows the right-hand rule.
B) The central axis should be held as the primary axis, and the top-plane's normal vector should be the secondary axis. The third axis follows the right-hand rule.
C) It doesn't matter whether the top-plane or the central axis is held as primary.

Question 7

A component, 4 meters in length, is installed on a beamline and surveyed. The center of the component is perfectly centered on the ideal beam axis, but the upstream end is 0.5 mm beam left and the downstream end is 0.5 mm beam right. How much is the component yawed?

A) 0.014 degrees
B) 0.007 degrees
C) 0.028 degrees
D) 0.005 degrees

Question 8

A component, 4 meters in length, is installed on a horizontal beamline and surveyed. The upstream end is 4 mm too high and the downstream end is 2 mm too low. To correctly align the component, how much vertical adjustment and pitch correction should be applied relative to the component's center?

A) Move downward 2 mm and pitch correct 0.172 degrees
B) Move downward 2 mm and pitch correct 0.115 degrees
C) Move downward 1 mm and pitch correct 0.172 degrees
D) Move downward 1 mm and pitch correct 0.086 degrees

Question 9

A fiducialized component has just been aligned to its ideal lattice position on the beamline using a laser tracker that was located in a coordinate system by observing a network of survey monuments. Which of the following is NOT an important step once component alignment is complete?

A) Check that the laser tracker was stable during the time it took to align the component by re-observing a survey network monument.
B) Check that the component is mechanically "locked down" so that it will hold its aligned position even if bumped.
C) Check that the laser tracker is completely warmed up.
D) Measure the as-aligned position of the fiducials and save the measurement data to a server that is backed up.

Question 10

Survey network floor monuments are being observed along a walkway with a laser tracker. The first two laser tracker positions are shown in the Figure 4. Of the three options shown in Figure 4, where should the next laser tracker be positioned (A, B, or C)?

Question 11

Refer back to the survey network scenario in Question 10. If only the two laser trackers are used in a least-squares network adjustment, what would the resulting uncertainty regions (error ellipses) look like? Would they look like "Error Ellipse Plot #1" (Figure 5) or "Error Ellipse Plot #2" (Figure 6)?

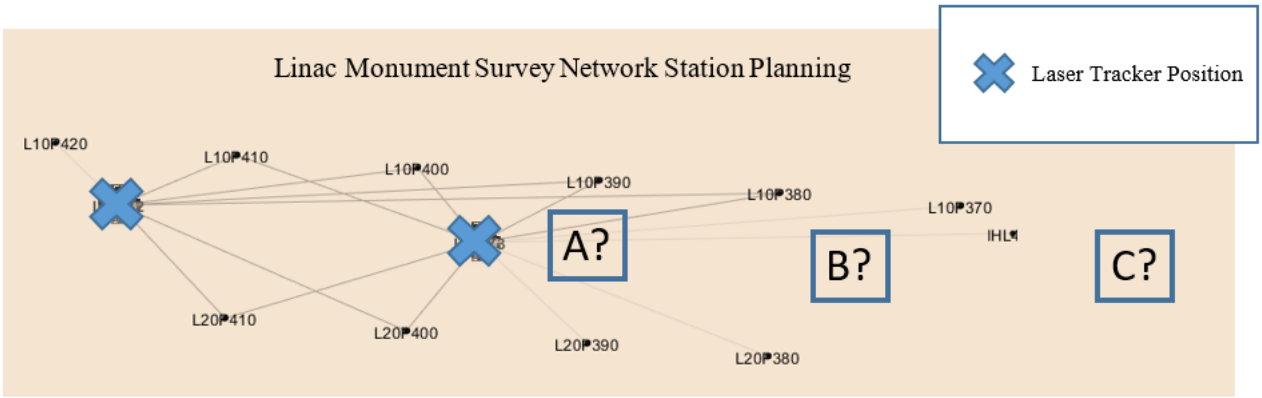

Figure 4: Survey station planning geometry for Question #10

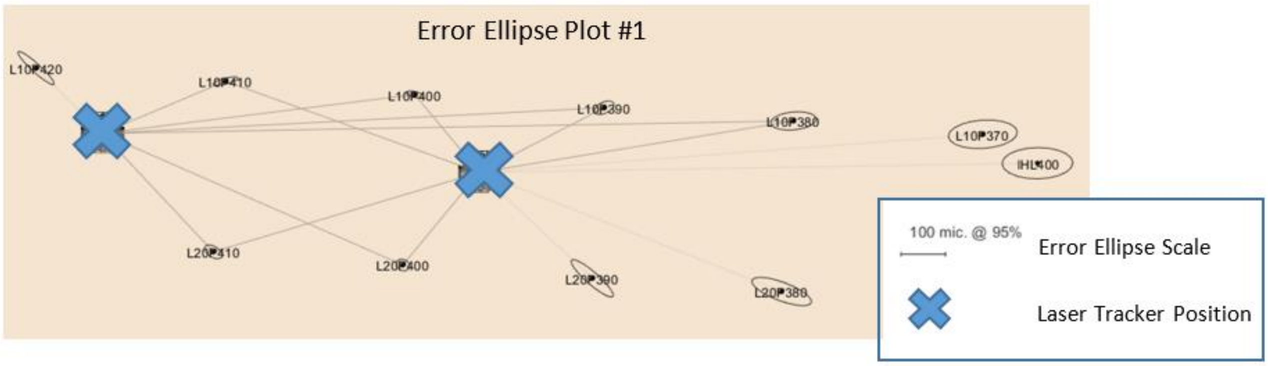

Figure 5: Error Ellipse Plot #1 for Question #11

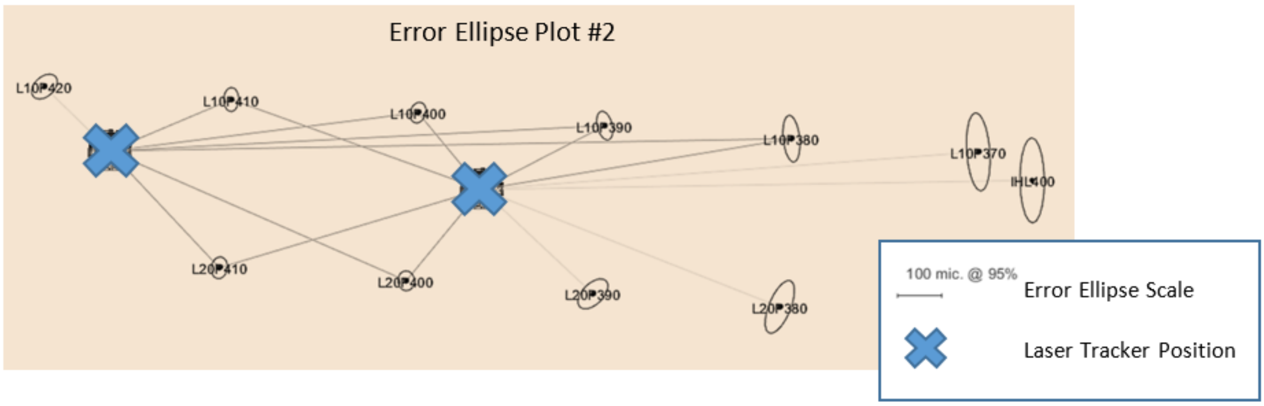

Figure 6: Error Ellipse Plot #2 for Question #11

Question 12

A laser tracker is positioned approximately 1 meter above the floor and measures 6 floor monuments to locate the instrument's position relative to the survey monument network (shown in Figure 7). To locate the laser tracker's position in the project's working coordinate system, a 6-parameter transformation (Tx, Ty, Tz, Rx, Ry, Rz) is applied to best-fit these 6 measurements to the known coordinates of these monuments. To improve the fit, it is suggested to recalculate the transformation by including a scaling term (a seventh parameter). The proposed scale factor, if applied, would scale all the measurements by 1.000020. If this scale factor is applied, what will happen to the newly calculated position of the laser tracker's height above the floor?

A) The laser tracker will have the same calculated height position in the network's coordinate system regardless of the scale factor.

B) More information is needed to determine what effect the scale factor would have on the calculated position of the laser tracker.

C) The calculated location of the laser tracker would be 20 microns higher if the proposed scale factor is applied compared to not applying the scale factor.

D) The calculated location of the laser tracker would be 20 microns lower if the proposed scale factor is applied compared to not applying the scale factor.

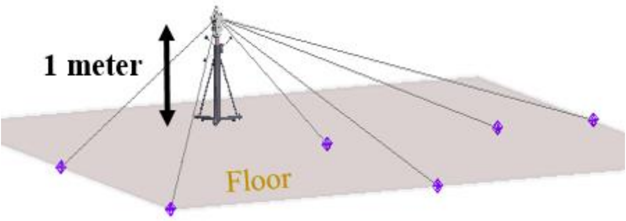

Figure 7: Floor Survey Geometry for Question #12

Question 13

Someone asks, "How well can your laser tracker measure distances?" To address this question, a repeatability test is set up. A laser tracker is placed ~5 meters away from an SMR and thirty distance measurements are taken in short secession. The sample standard deviation of the measurements is +/- 3 microns. What can be said about the instrument's measurement capability from these test results?

A) The accuracy of the laser tracker's distance measurements is +/- 3 microns.
B) The accuracy of the laser tracker's distance measurements is +/- 3 microns at a range of 5 meters.
C) The magnitude of the random errors associated with the laser tracker's distance measurements (excluding possible systematic errors that may be present) is +/- 3 microns at a range of 5 meters.
D) The magnitude of the random errors associated with the laser tracker's distance measurements (excluding possible systematic errors that may be present) under identical setup and environmental conditions is +/- 3 microns at a range of 5 meters.

Question 14

A magnet has 4 fiducials (circled in orange in Figure 8).

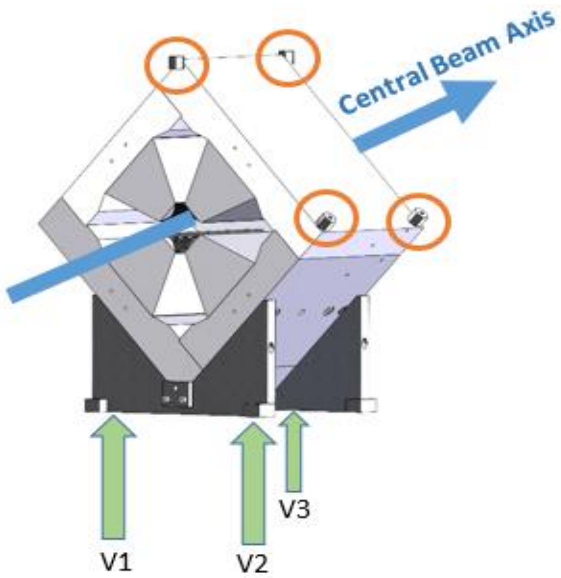

Figure 8: Fiducial Locations for Question 14

It also has three vertical adjuster screws (V1, V2, V3) to adjust the pitch, roll, and height. Adding a fifth fiducial to the magnet is proposed to the design. Is there any value in adding another one? Option (A) would decline to add another fiducial and retain only the four fiducials. If another fiducial is added (Options B, C, or D), where should it be placed? Assume that each of the proposed positions (each option shown in Figure 9 circled in orange) would be accessible and visible for the fiducialization and alignment procedures.

A) Decline to add any more fiducials
B) Choose option B shown in Figure 9
C) Choose option C shown in Figure 9
D) Choose option D shown in Figure 9

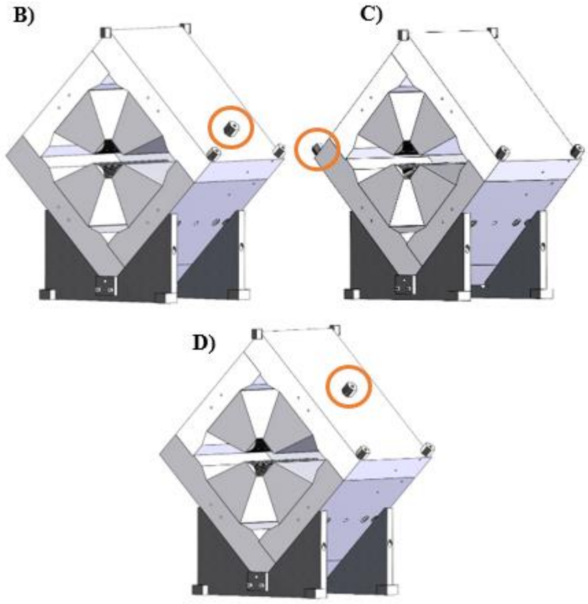

Figure 9: Optional Fiducial Placement for Question 14

Question 15

An existing beamline with hundreds of magnets has been in good operation for five years. Before its first commissioning, all the magnets were aligned within a component-to-component tolerance specification of 0.1 mm. A large-scale survey campaign was taken five years later to re-observe the monument network and magnet positions for this entire beamline. The positions of the magnets from five years ago were updated with new coordinates from the analysis and adjustment of the new survey data. Comparing the new coordinates of the magnet positions to the ones previously established reveals $\Delta X, \Delta Y, \Delta Z$ values between the two epochs. Many of the delta values are larger than the acceptable component-to-component alignment tolerances. What further analysis should be done?

A) Request that the accelerator physicists re-evaluate the alignment tolerance specifications.
B) Identify all magnets with $\Delta X, \Delta Y, \Delta Z$ values larger than 0.1 mm and realign them.
C) Look at the trend (i.e. curve fitting) of the $\Delta X, \Delta Y, \Delta Z$ values along the beamline and identify any possible magnet outliers that are more than 0.1 mm from the trendline for re-alignment consideration.
D) Identify magnets with the largest $\Delta X, \Delta Y, \Delta Z$ values and re-align as many of those as you can.

ANSWERS

Answer 1

B is correct. P2 is the most accurately measured point because it is closest to the laser tracker and is in the middle of the network monuments used to locate the laser tracker. P1 is farther away than P2, so it is less accurate. P1 is also not as close to the middle of the monuments, but the principle of interpolation still applies. P3 is not within the bounds of the monuments used to locate the instrument and is, therefore, the least accurately located point in the working coordinate system. The coordinates of P3 are conceptually determined by an extrapolation (not interpolation) of the network of monuments used to locate the instrument. The cardinal principle of surveying is to work "from whole-to-part" (i.e. interpolation) instead of from "part-to-whole" (i.e. extrapolation) [1]. The surveying principle of working from "whole-to-part" is developed in introductory terms in the first chapter of Plane Surveying by Alak De [2].

Answer 2

All except D. Although asking whether a component's fiducials have been measured yet is important, it is unrelated to designing or prototyping a component's alignment adjuster system.

Answer 3

C is correct. The flatness is the distance between the two largest deviations (-2.3 mm and 3.0 mm) which is 5.3 mm. The technical definition of flatness, defined by the American Society of Mechanical Engineers in ASME Y14.5.1M-1994, "specifies a tolerance zone defined by two parallel planes within which the surface must lie" [3].

The RMS is the square root of the mean of squared deviations:

$$\text{RMS} = \sqrt{\frac{0.7^2 + 0.7^2 + 0.3^2 + 2.3^2 + 0.8^2 + 3.0^2 + 0.2^2}{7}} = 1.5$$

Answer 4

C is correct. Balancing the foresight and backsight lengths mitigates errors from systematic errors. See section 5.37, "Balancing Backsights and Foresight Distances," of *Surveying Theory and Practice* for more on this [4]. Because a height difference (ΔH) between two monuments is equal to the backsight reading (BS) minus the foresight reading (FS), systematic errors (e) that are a function of distance will cancel each other out as shown below:

$$\Delta H = (BS + e) - (FS + e)$$
$$\Delta H = BS + e - FS - e$$
$$\Delta H = BS - FS$$

Answer 5

A is correct. A two-peg test will determine whether the instrument's sightings are level.

Answer 6

B is correct. Because the central axis and the top-plane normal vector are not perfectly orthogonal ($90.02 \neq 90$), it is impossible to perfectly position the central axis on the horizontal beamline and also place the top-plane's normal vector pointing straight up. If the angle between them was exactly 90 degrees, choosing which to hold as primary would not matter. Because the pitch requirement was desired to be defined by the central axis (and not by the top-plane), it is necessary to make the central axis the primary axis. For more study on the effect of choosing the primary axis, research the Gram-Schmidt process, holding the primary axis as the first vector to define the set of mutually orthogonalized vectors. Chapter 14 of *Numerical Linear Algebra with Applications* describes the Gram-Schmidt process in detail [5].

Answer 7

A is correct. Use the formula $\theta\ (rad) = \frac{S}{R}$ where S is 0.5 mm and R is half the length (2 m) and convert to degrees:

$$\text{Yaw} = \frac{0.0005\ (\text{m})}{2\ (\text{m})} \frac{180\ degrees}{\pi\ radians} = 0.014\ degrees$$

Answer 8

D is correct. The average between 4 mm too high (+ 4mm) and 2 mm too low (- 2mm) is "too high" by 1 mm (+ 1mm). Therefore, the component as a whole needs to come down 1 mm. Once the component as a whole is moved down 1mm, the upstream end will need to move down another 3 mm, while the downstream end will need to move up 3 mm.

Use the formula $\theta\ (rad) = \frac{S}{R}$ where S is 3 mm and R is half the length (2 m) and convert to degrees:

$$\text{Pitch correction} = \frac{0.003\ (\text{m})}{2\ (\text{m})} \frac{180\ degrees}{\pi\ radians} = 0.086\ degrees$$

Answer 9

C is correct. The laser tracker should have already been warmed up before the alignment process was started.

Answer 10

B is correct. Laser tracker positions should be evenly spaced to provide homogenous network accuracy (not position A). The next tracker position should be placed behind the farthest points measured from the previous setup. This ensures that monuments are measured at least three times and that the triangulation of the survey network does not have angles that are too obtuse (not position C). For a case study on designing a homogeneous laser tracker survey network with uniform accuracy, see "Three-Dimensional Network Adjustment of Laser Tracker Measurements for Large-Scale Metrology Applications" [6].

Answer 11

Error Ellipse Plot #2 is correct. Laser trackers measure distances more accurately than angles. Therefore, the major axis of error ellipses is perpendicular to the lines of sight as shown in Error Ellipse Plot #2. See section 19.1, titled "Error Ellipse," in *Adjustment Computations: Spatial Data Analysis, Fifth Edition*, by Charles D. Ghilani for more details on the multivariate normal distribution of coordinates derived from survey measurements [7].

Answer 12

C is correct. Because all of the measured distances will be scaled by 1.000020, every height component of the measurements will be scaled 20 microns per meter of height. All 6 measurements will have height components of ~1 meter which will be scaled by an additional 20 microns in the height dimension. This will result in a calculated instrument position that is 20 microns higher than without scaling the measurements.

Answer 13

D is correct. The accuracy of distance measurements has a parts-per-million (ppm) aspect where accuracy goes down with increased range. See Eq. 7.38 in *Adjustment Computations Spatial Data Analysis* for more on this [7]. Therefore, accuracy is not the same at all ranges (not choice A). Systematic errors will affect all thirty repeated measurements by roughly the same magnitude and therefore do not affect the variance of the test's sample set (not choice B). Repeated measurements under identical setup and environmental conditions will yield smaller observation variances than if these factors are varied (not choice C). For further review of how measurement uncertainties and repeatability testing of laser tracker measurements relate, see "A New Modeling Approach for A Priori Uncertainties of Laser Tracker Angle Measurements" [8].

Answer 14

C is correct. While the minimum number of fiducials mathematically necessary to determine a rigid body's 3D position is three, more than three is preferred. Redundancy (more than three) is needed to catch outliers in the fiducialization, alignment, and surveying steps. Even four fiducials is not usually ideal. The four original positions are all on one side of the magnet which is also not preferred. Ideally, fiducials are placed to surround the magnet's center so that relating the center to the fiducials is conceptually an interpolation. Fiducial configuration options A, B, and D do not surround the magnet's center (conceptually extrapolation). Option C is preferred and also provides a good dynamic reference during the alignment phase to set the height of the Beam-Left side of the magnet using the V1 height adjuster.

Answer 15

C is correct. The absolute accuracy of coordinates derived from two independent large-scale surveys is less accurate than the comparison of localized relative positions. Wholesale re-alignment of existing beamlines using absolute positions is "nonsense" [9]. Smoothing techniques are used to analyze relative displacements from the absolute trend curve for re-alignment. Low-degree polynomial fits over a local "sliding window" is usually used—comparable to a carpenter's plane used for smoothing an irregular plank [10]. See Figures 8 and 9 in "Progress Report for the Advanced Photon Source Upgrade Project" for an example of a trend line in the vertical and horizontal dimensions [11].

CONCLUSION

In conclusion, this paper has presented key alignment concepts and a tool for professional development within the accelerator alignment community. The multiple-choice format has been designed to engage newer alignment engineers to review these accelerator alignment topics. The included explanations are intended to inspire further exploration and learning. More such questions and answers from Survey & Alignment groups from other laboratories are encouraged and welcomed to be shared! Sharing learning strategies for continuous development between laboratories will enhance the professional growth of members in our specialized field.

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