A Survey of Accelerator Alignment Concepts for Professional Development
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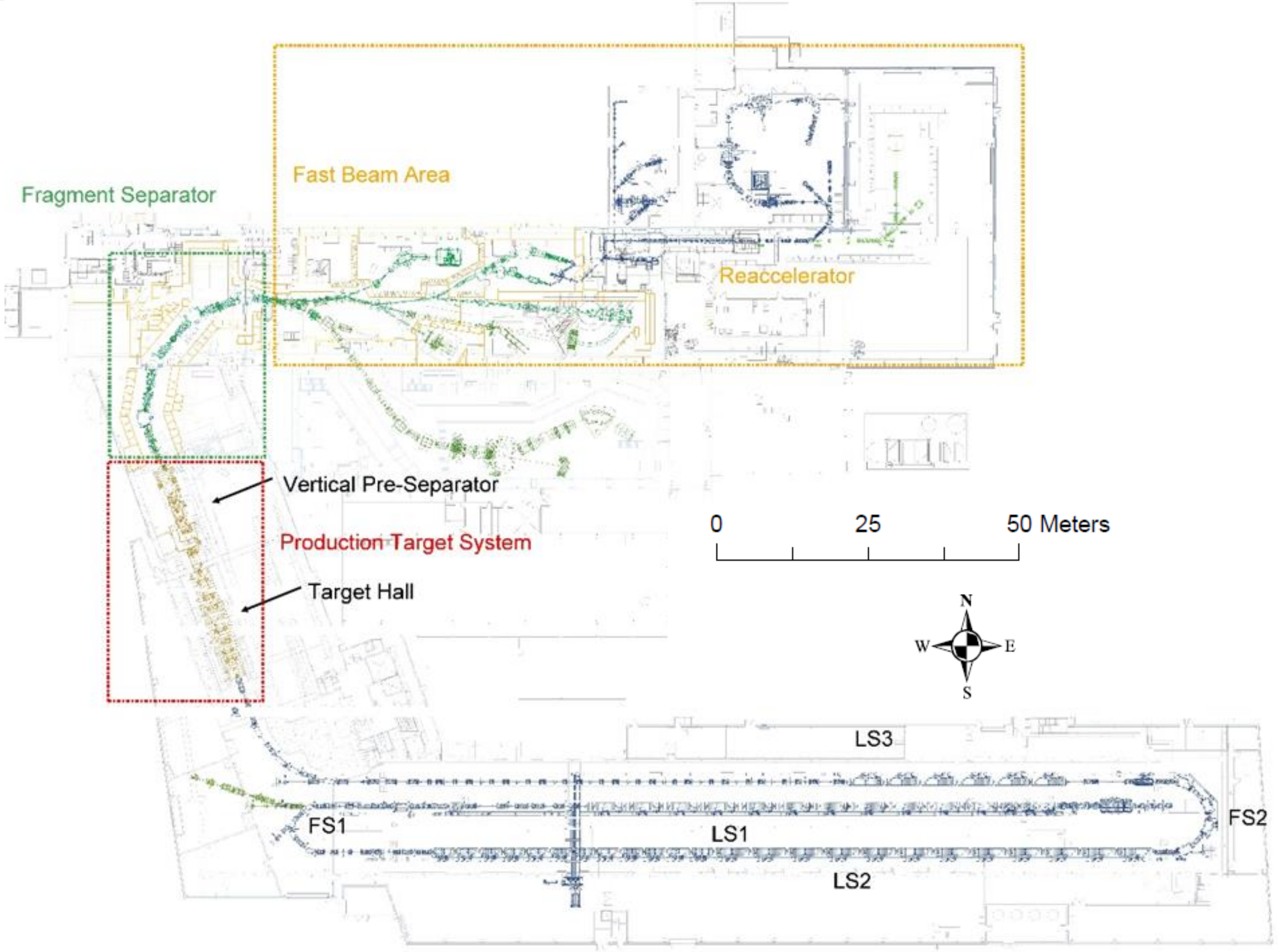
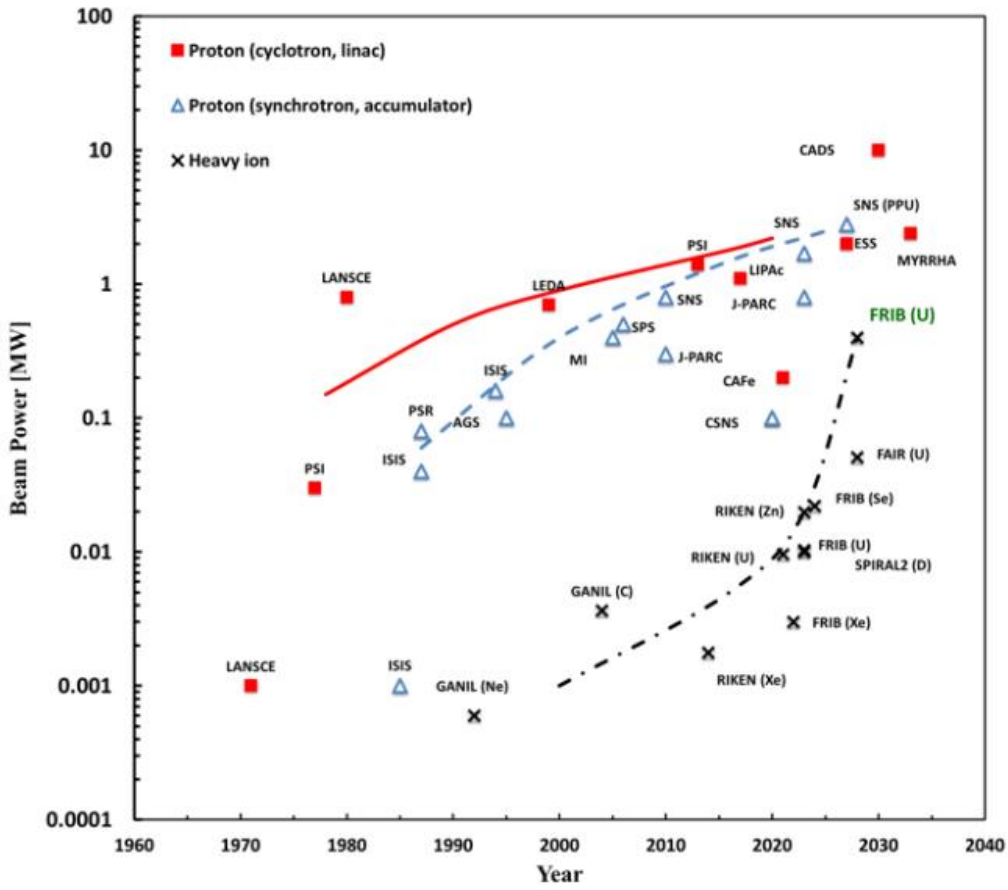
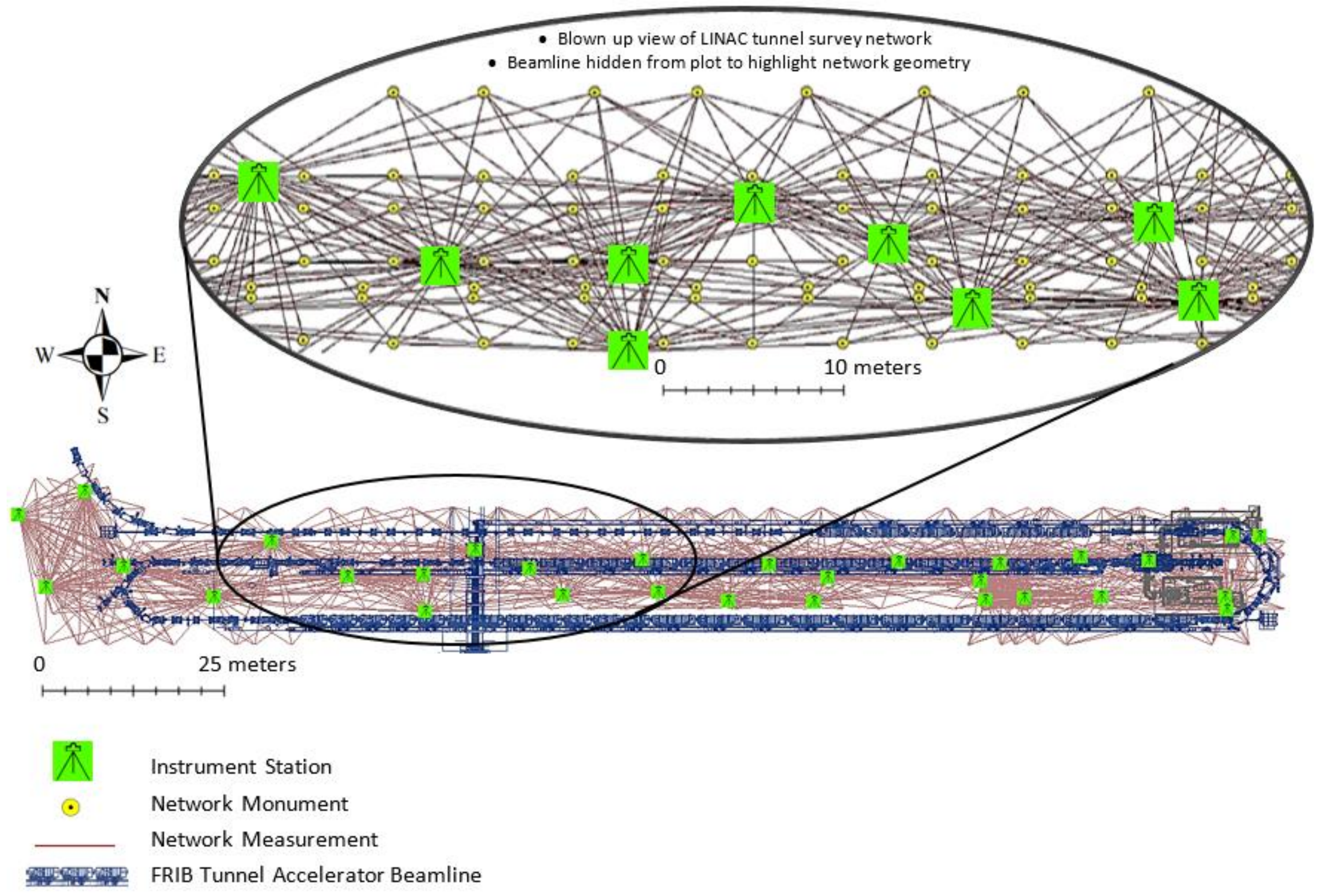
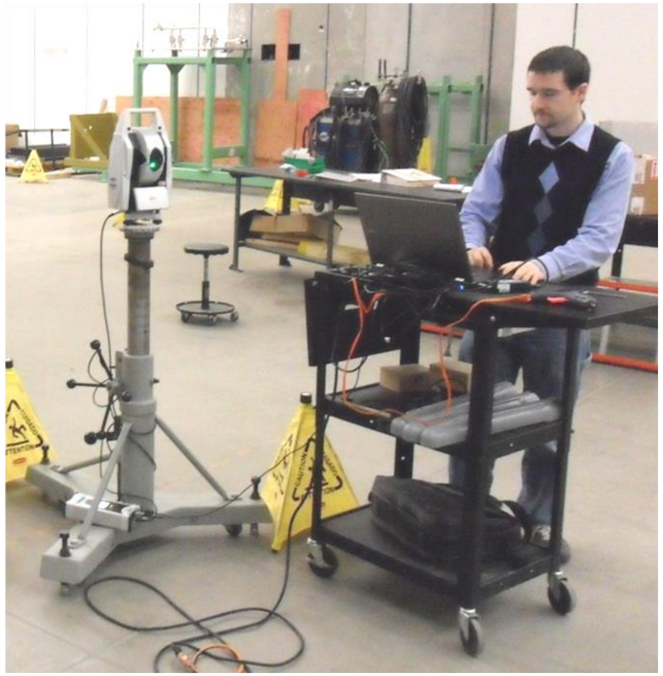




Example of Survey Network Measurements





Professional Development

- Within labs, professional development is often required.
- Limited introductory resources are available within the accelerator alignment community that address the unique considerations of this specialized discipline.
- The paper accompanying this presentation 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.
- Not meant to be overly difficult.

Topics Covered

- Network survey planning
- Geometric impacts on measurement accuracy
- Fiducialization techniques
- Alignment smoothing
- Geometric Dimensioning
- For this presentation, we will look at the Questions and Answers for problems #1, #6, #10, #11, #14, #15 from the quiz.

Question 1

Q: 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.

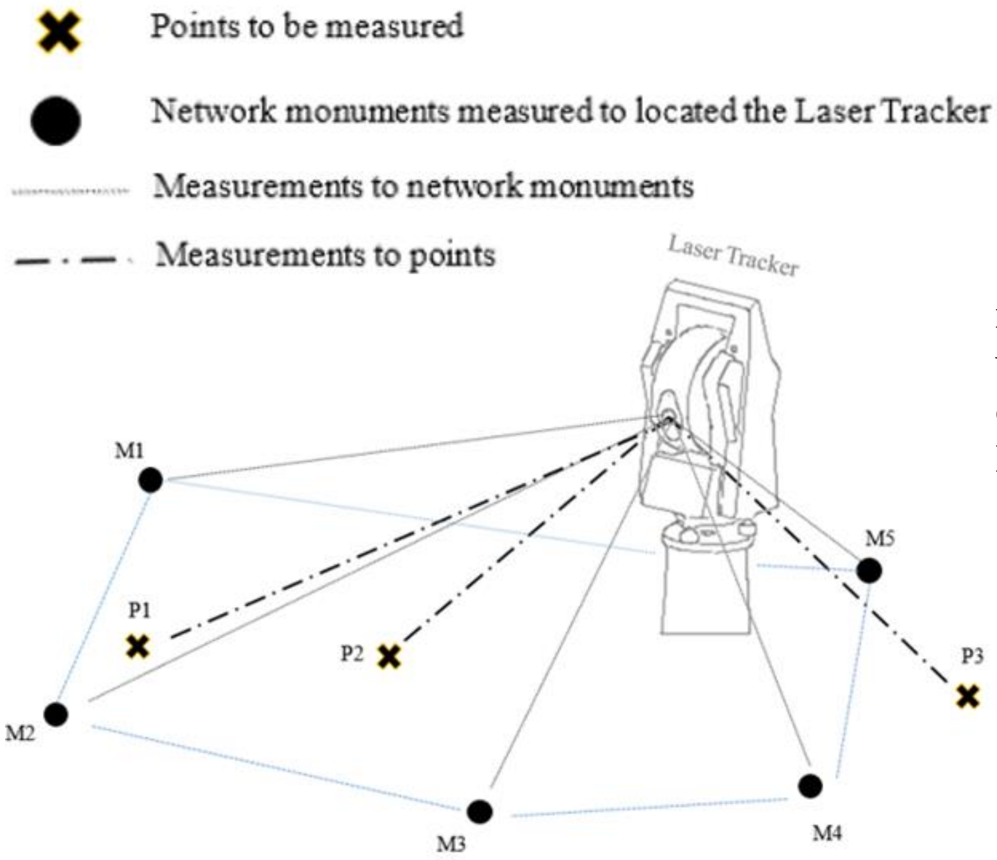


Figure 1: Survey Geometry for Question #1

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

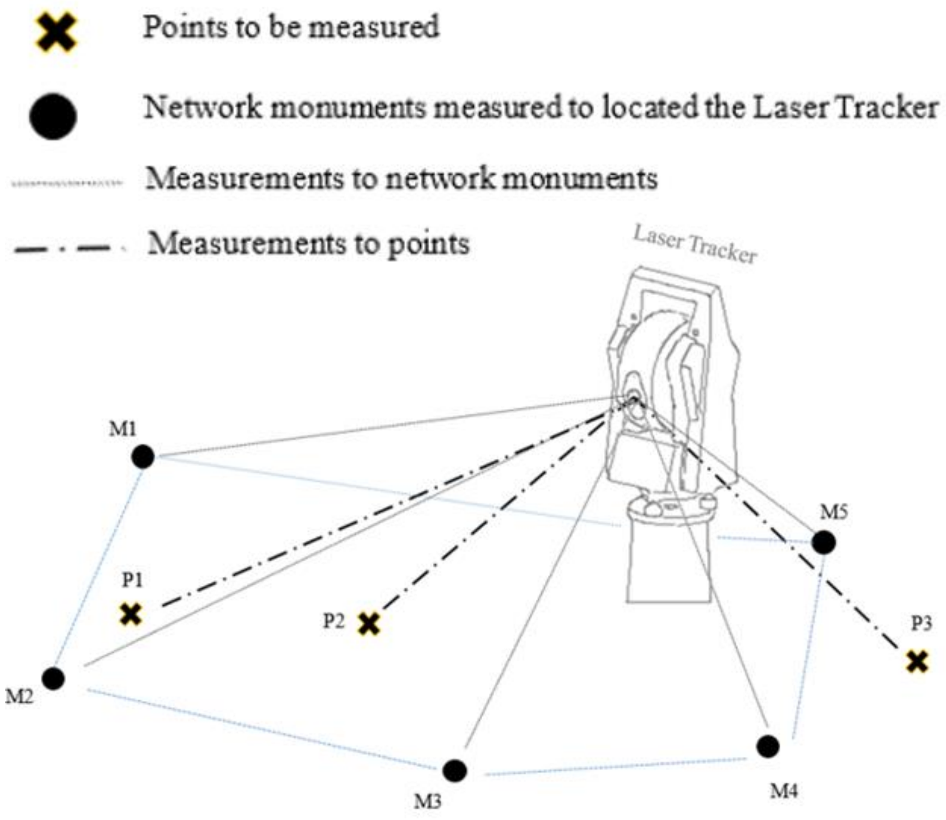
Answer 1

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].

[1] Byrne, P., & Kelly, G. (2007). The ABC of x,y,z - 21 Principles for Consideration by Surveyors and Other Geospatial Professionals. International Federation of Surveyors.

[2] De, A. (2000). Plane Surveying. New Delhi: S. Chand & Company.



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

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.

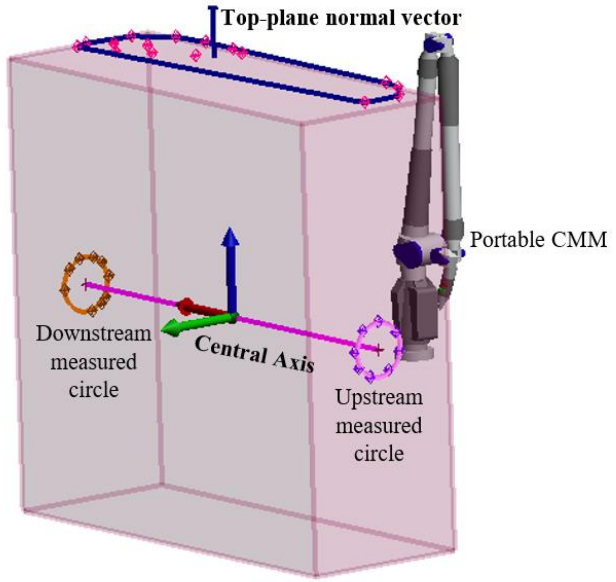


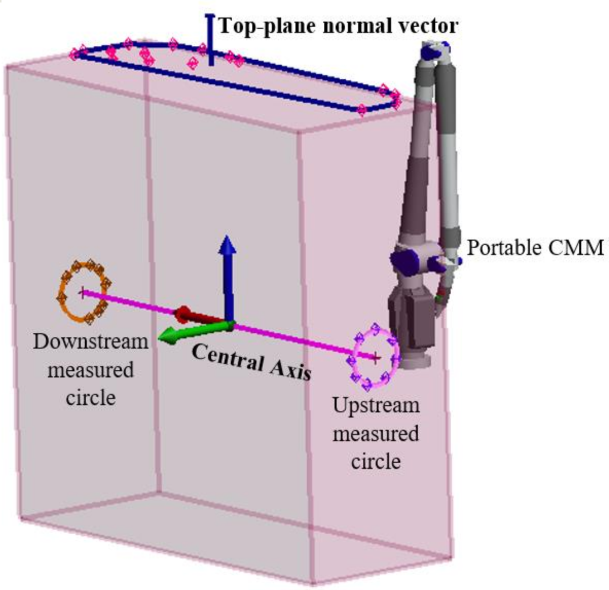
Figure 3: Magnet Fiducialization Measurements

Using the fiducialization data, how should the ideal placement be determined?

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 mid-plane or the central axis is held as primary.

Answer 6

B is correct. Because the central axis and the top-plane normal vector are not perfectly orthogonal (90.02 ≠ 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].



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.

[5] Ford, W. (2015). Numerical Linear Algebra with Applications. Academic Press.

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)?

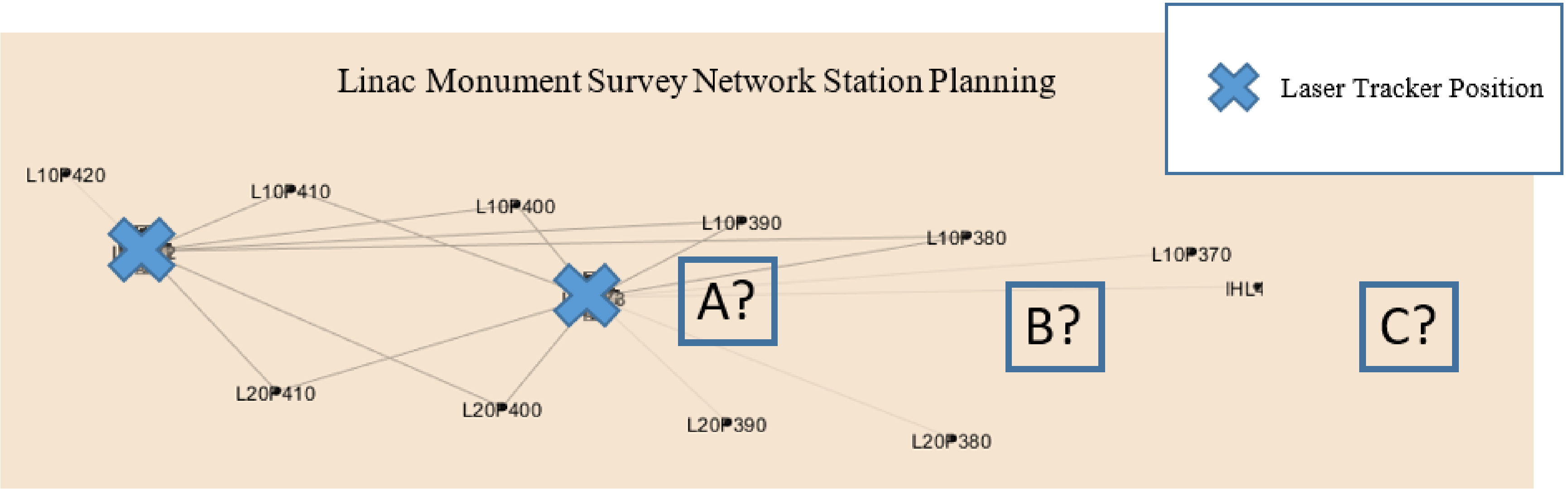


Figure 4: Survey station planning geometry

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].

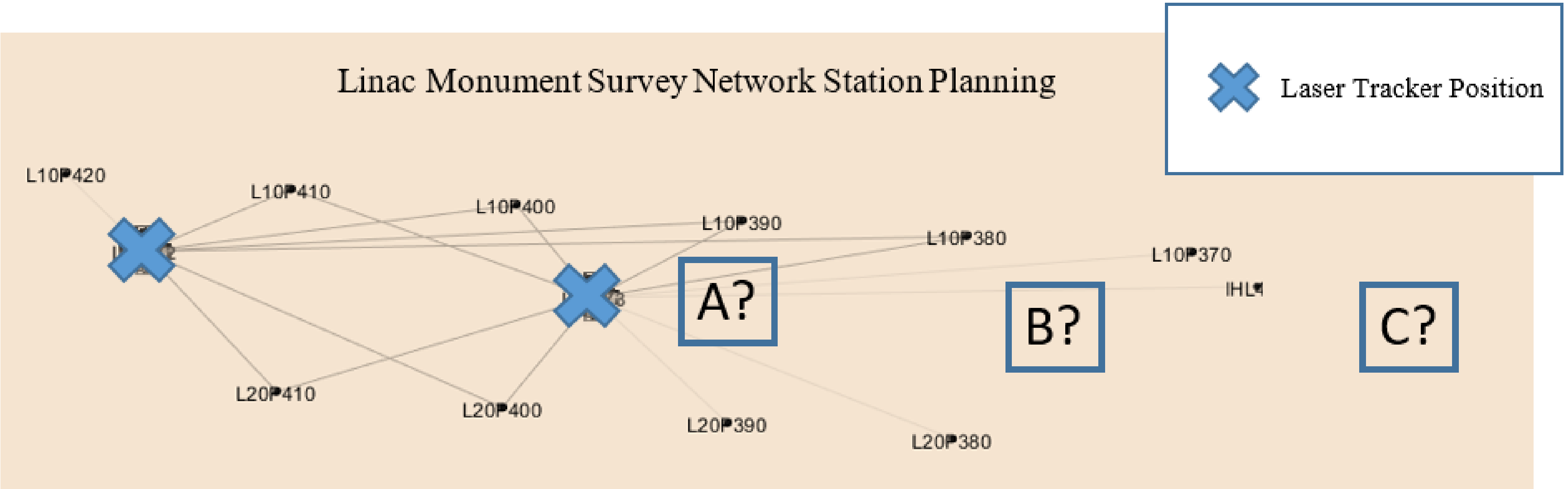


Figure 4: Survey station planning geometry

[6] Manwiller, P. (2020, September 26). Three-Dimensional Network Adjustment of Laser Tracker Measurements for Large-Scale Metrology Applications. Journal of Surveying Engineering, 147(1). doi:10.1061/(ASCE)SU.1943-5428.0000332.

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 5: Error Ellipse Plot #1

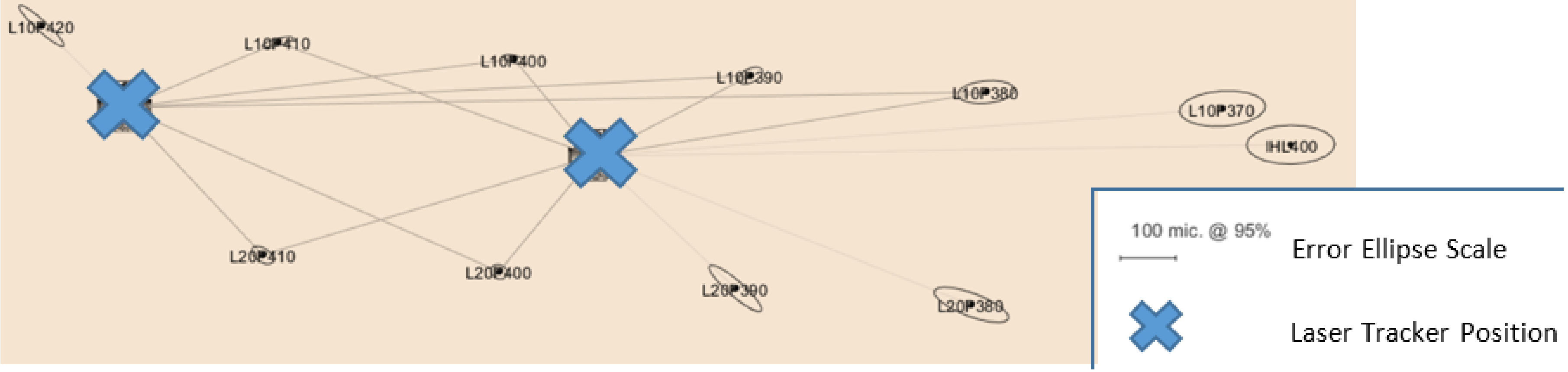
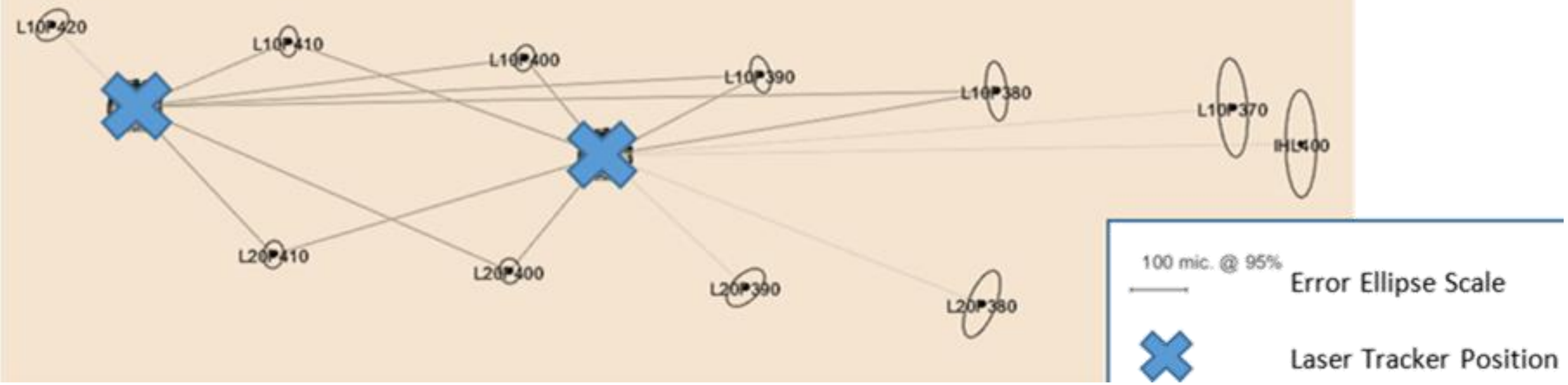


Figure 6: Error Ellipse Plot #2



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].

Figure 5: Error Ellipse Plot #1

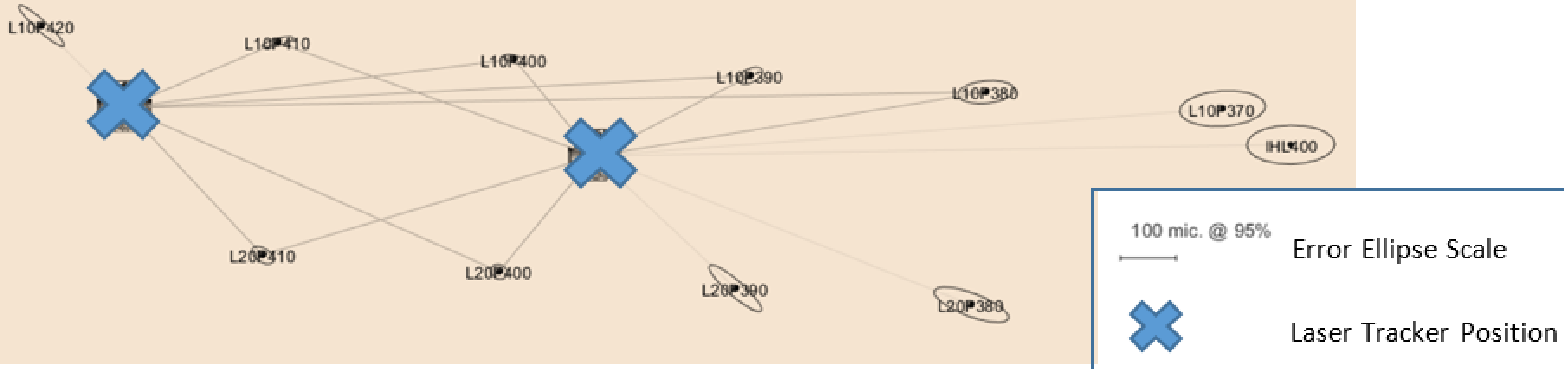
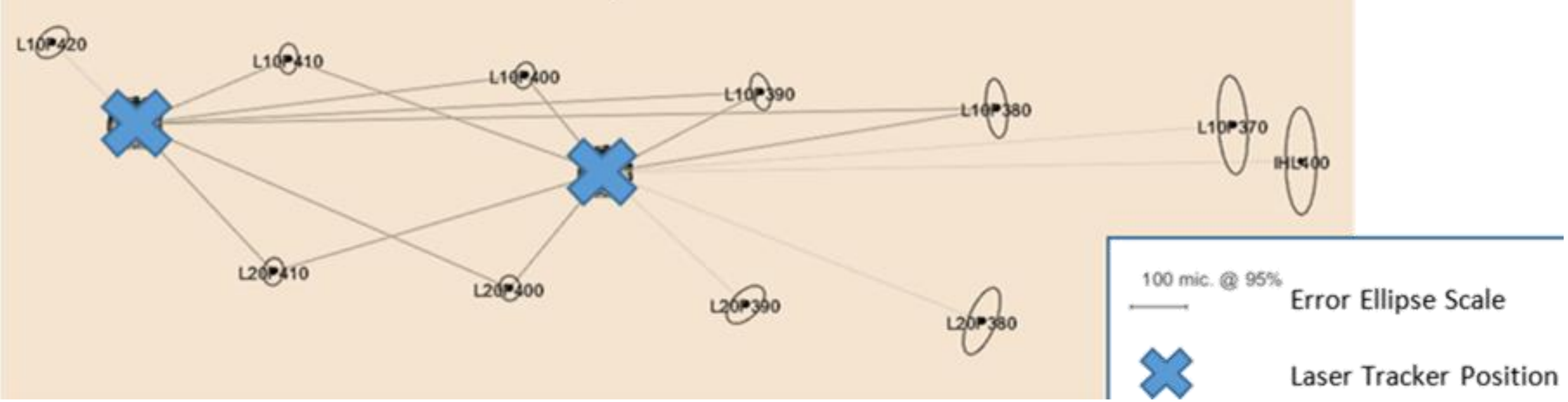


Figure 6: Error Ellipse Plot #2



[7] Ghilani, C. D. (2010). Adjustment Computations: Spatial Data Analysis (Fifth Edition ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Question 14

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

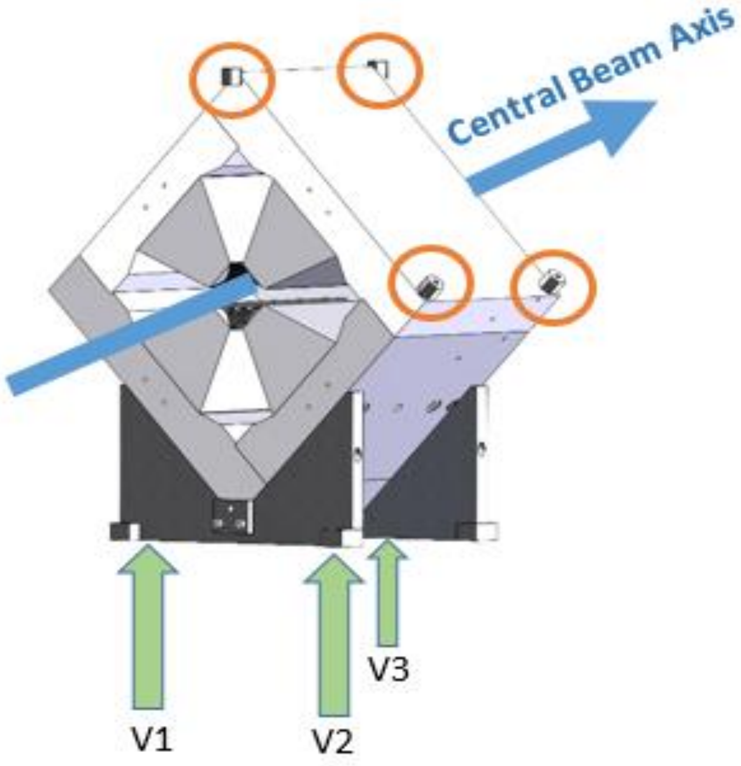
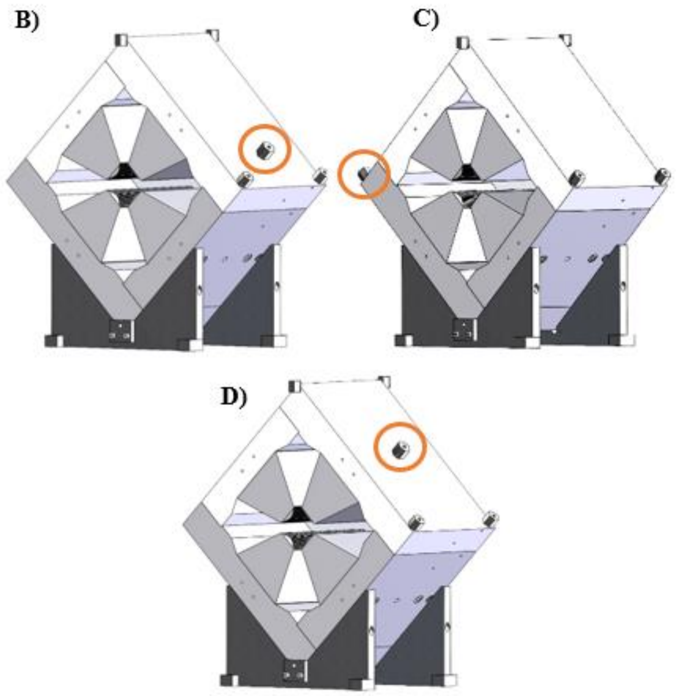


Figure 8: Fiducial Locations for Question 14

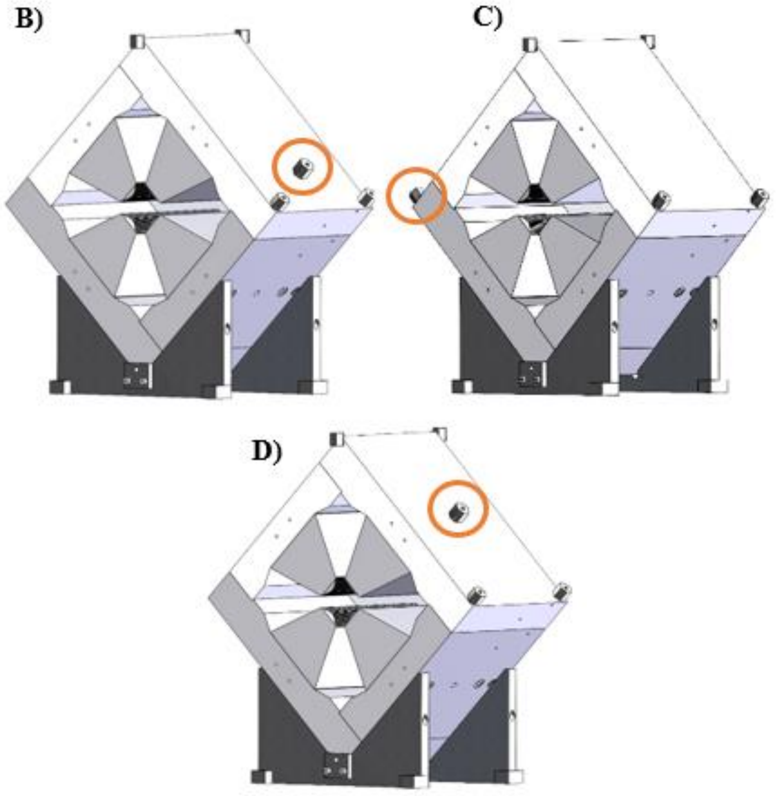


A) Decline to add any more fiducials
B) Choose option B shown in Figure 9
C) Choose option C shown in Figure 9
D) Choose option D shown in Figure 9

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.



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.

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].

[9] Ruland, R. E. (1991). Accelerator and Transport Line Survey and Alignment. Menlo Park, CA: SLAC National Accelerator Laboratory (SLAC). Retrieved from https://www.osti.gov/biblio/1449626

[10] Mayoud, M. (1997). Measurement and Alignment of Accelerator and Detector Magnets. CERN Accelerator School. Geneva, Switzerland. doi:e-proceedings: 10.5170/CERN-1998-005.

[11] Jansma, B. (2022). Progress Report for the Advanced Photon Source Upgrade Project. International Workshop on Accelerator Alignment (IWAA). Ferney-Voltaire, France.

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D) Identify magnets with the largest $\Delta X, \Delta Y, \Delta Z$ values and re-align as many of those as you can.

Summary

- For this presentation, we looked at Questions and Answers for problems #1, #6, #10, #11, #14, #15 from the quiz.
- 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.
- More such Questions and Answers from Survey & Alignment groups from other laboratories are welcomed to be shared!