ASPRS Positional Accuracy Standards for Digital Geospatial Data

EDITION 2, VERSION 1.0 - August 23, 2023

Adopted by ASPRS Board of Directors on August 23, 2023

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ASPRS Positional Accuracy Standards for Digital Geospatial Data

(EDITION 2, VERSION 1.0 - AUGUST 2023)

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FOREWORD

Edition 1 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data was published in November 2014. In the years since, users expressed concerns and suggested revisions based on their experience applying the Standards in real-world situations. In addition, technologies have evolved in such a way as to challenge the assumptions upon which Edition 1 was based.

In 2022, ASPRS established a formal Positional Accuracy Standards Working Group under the Standards Committee to evaluate user comments, consider technology advancements, and implement appropriate changes to the Standards. The following individuals were appointed to the Positional Accuracy Standards Working Group:

Chair: Dr. Qassim Abdullah, Vice President and Chief Scientist, Woolpert, Inc.

Members:

- Dr. Riadh Munjy, Professor of Geomatics Engineering, California State University, Fresno
- Josh Nimetz, Senior Elevation Project Lead, U.S. Geological Survey
- Michael Zoltek, National Geospatial Programs Director, GPI Geospatial, Inc.
- Colin Lee, Photogrammetrist, Minnesota Department of Transportation

The ASPRS Positional Accuracy Standards for Digital Geospatial Data are designed to be modular in nature, such that revisions could be made and additional sections added as geospatial technologies and methods evolve. Additionally, the Standards are designed to recommend best practices, methods, and guidelines for the use of emerging technologies to achieve the goals and requirements set forth in the Standards. With support from the ASPRS Technical Divisions, the primary Working Group established subordinate Working Groups to author Addenda for best practices and guidelines for photogrammetry, lidar, UAS, and field surveying. The subordinate Working Group members and contributors are credited in each Addendum, as appropriate.

Summary of Changes in Edition 2

Important changes adopted in Edition 2 of the Standards are as follows:

1. Eliminated references to the 95% confidence level as an accuracy measure.

    . *Reason for the change*: The 95% confidence measure of accuracy for geospatial data was introduced in the National Standard for Spatial Data Accuracy (NSSDA) published by the Federal Geographic Data Committee in 1998. This measure was carried forward in the ASPRS Guidelines for Vertical Accuracy Reporting for Lidar Data published in 2004, as well as in Edition 1 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data published in 2014. However, RMSE is also a way to express data accuracy, and it is typically reported alongside the 95% confidence level because the two are derived from the same error distribution. As a matter of fact, users need to compute RMSE first in order to obtain the 95% confidence measure. The reporting of two quantities representing the same accuracy at different confidence levels has created confusion for users and data producers alike.

. *Justification for the change*: The RMSE is a reliable statistical term that is sufficient to express product accuracy, and it is well understood by users. Experience has shown that the use of both RMSE and the 95% confidence level leads to confusion and misinterpretation.

2. Relaxed the accuracy requirement for ground control and checkpoints.

. *Reason for the change:* Edition 1 called for ground control points of four times the accuracy of the intended final product, and ground checkpoints of three times the accuracy of the intended final product. With goals for final product accuracies approaching a few centimeters in both the horizontal and vertical, it becomes difficult, if not impossible, to use RTK methods for control and checkpoint surveys, introducing a significant burden of cost for many high-accuracy projects.

. *Justification for the change:* As the demand for higher-accuracy geospatial products grows, accuracy requirements for the surveyed ground control and checkpoints set forth in Edition 1 exceed those that can be achieved in a cost-effective manner, even with high-accuracy GPS. Furthermore, today's sensors, software, and processing methods have become very precise, diminishing the errors introduced in data acquisition and processing. If best practices are followed, safety factors of three and four times the intended product accuracy are no longer needed.

3. Required the inclusion of survey checkpoint accuracy when computing the accuracy of the final product.

. *Reason for the change:* Since checkpoints will no longer need to meet the three-times-intended-product accuracy requirement (see item 2 above), the error in the checkpoints survey may no longer be ignored when reporting the final product accuracy. This is especially important, given the increasing demand for highly accurate products—which, in some cases, approach the same order of magnitude as the survey accuracy of the checkpoints. Therefore, checkpoint error should be factored into the final product accuracy assessment that is used to communicate the reliability of resulting final products.

. *Justification for the change:* Errors in the survey checkpoints used to assess final product accuracy, although small, can no longer be neglected. As product accuracy increases, the impact of error in checkpoints on the computed product accuracy increases. When final products are used for further measurements, calculations, or decision making, the reliability of these subsequent measurements can be better estimated if the uncertainty associated with the checkpoints is factored in.

4. Removed the pass/fail requirement for Vegetated Vertical Accuracy (VVA) for lidar data.

. *Reason for the change*: Data producers and data users have reported that they are challenged in situations where Non-Vegetated Vertical Accuracy (NVA) is well within contract specifications, but VVA is not. As explained below, factors affecting VVA are not a function of the lidar system accuracy; therefore, only NVA should be used when making a pass/fail decision for the overall project. VVA should be evaluated and reported, but should not be used as a criterion for acceptance.

- *Justification for the change*: Where lidar can penetrate to bare ground under trees, the accuracy of the points, as a function of system accuracy, should be comparable to lidar points in open areas. However, the accuracy and the quality of lidar-derived surface under trees is affected by:
- 1) the type of vegetation where it affects the ability of lidar pulse to reach the ground,
- 2) the density of lidar points reaching the ground,
- 3) and the performance of the algorithms used to separate ground and above-ground points in these areas.
- Furthermore, the accuracy of the ground checkpoints acquired with GPS surveying techniques in vegetated areas is affected by restricted satellite visibility. As a result, accuracies computed from the lidar-derived surface in vegetated areas are not valid measures of lidar system accuracy.

5. Increased the minimum number of checkpoints required for product accuracy assessment from 20 to 30.
   - *Reason for the change:* In Edition 1, a minimum of 20 checkpoints are required for testing positional accuracy of the final mapping products. This minimum number is not based on rigorous science or statistical theory; rather, it is a holdover from legacy Standards and can be traced back to the National Map Accuracy Standards published by the U.S. Bureau of the Budget in 1947.
   - *Justification for the change:* The Central Limit Theorem calls for at least 30 samples to calculate statistics such as mean, standard deviation, and skew. These statistics are relied upon in positional accuracy assessments. According to The Central Limit Theorem, regardless of the distribution of the population, if the sample size is sufficiently large ($n \geq 30$), then the sample mean is approximately normally distributed, and the normal probability model can be used to quantify uncertainty when making inferences about a population based on the sample mean. Therefore, in Edition 2, a product accuracy assessment must have a minimum number of 30 checkpoints in order to be considered fully compliant.
6. Limited the maximum number of checkpoints for large projects to 120.
   - *Reason for the change:* Since these Standards recognize the Central Limit Theorem as the basis for statistical testing, there is insufficient evidence for the need to increase the number of checkpoints indefinitely as the project area increases. The new maximum number of checkpoints is equal to four times the number called by the Central Limit Theorem.
   - *Justification for the change:* According to the old guidelines, large projects require hundreds, sometimes thousands of checkpoints to assess product accuracy. Such numbers have proven to be unrealistic for the industry, as it inflates project budget and, in some cases, hinders project executions, especially for projects taking place in remote or difficult-to-access areas.
7. Introduced a new accuracy term: “three-dimensional positional accuracy."

. *Reason for the change:* Three-dimensional models require consideration of three-dimensional accuracy, rather than separate horizontal and vertical accuracies. Edition 2 endorses the use of the following three terms:

- Horizontal positional accuracy
- Vertical positional accuracy
- Three-dimensional (3D) positional accuracy

. *Justification for the change*: Three-dimensional models and digital twins are gaining acceptance in many engineering and planning applications. Many future geospatial data sets will be in true three-dimensional form; therefore, a method for assessing positional accuracy of a point or feature within the 3D model is needed to support future innovation and product specifications.

8. Added Best Practices and Guidelines Addenda for:

   - General Best Practices and Guidelines
   - Field Surveying of Ground Control and Checkpoints
   - Mapping with Photogrammetry
   - Mapping with Lidar
   - Mapping with UAS

This summarizes the most significant changes implemented in Edition 2 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data. Other minor changes will be noted throughout.

Foreword to Edition 1 of 2014

The goals of American Society for Photogrammetry and Remote Sensing (ASPRS) are: to advance the science of photogrammetry and remote sensing; to educate individuals in the science of photogrammetry and remote sensing; to foster the exchange of information pertaining to the science of photogrammetry and remote sensing; to develop, place into practice, and maintain standards and ethics applicable to aspects of the science; to provide a means for the exchange of ideas among those interested in the sciences; and to encourage, publish and distribute books, periodicals, treatises, and other scholarly and practical works to further the science of photogrammetry and remote sensing.

These Standards were developed by the ASPRS Map Accuracy Standards Working Group, a joint committee under the Photogrammetric Applications Division, Primary Data Acquisition Division, and Lidar Division. The Working Group was formed for the purposes of reviewing and updating ASPRS map accuracy Standards to reflect current technologies. A subcommittee of this group, consisting of Dr. Qassim Abdullah of Woolpert, Inc., Dr. David Maune of Dewberry Consultants, Doug Smith of David C. Smith and Associates, Inc., and Hans Karl Heidemann of the U.S. Geological Survey, was responsible for drafting the document.

ASPRS Positional Accuracy Standards for Digital Geospatial Data

(EDITION 2, VERSION 1.0 - FEBRUARY 2023)

1. PURPOSE

The objective of Edition 2 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data is to update Edition 1 of the Standards.

These Standards include positional accuracy standards for digital orthoimagery, digital planimetric data, and digital elevation data. Accuracy classes, based on RMSE values, have been revised and upgraded from the 1990 Standards to address the higher accuracies and higher spatial resolutions achievable with newer technologies. Edition 2 also introduces additional accuracy measures, such as orthoimagery seam lines, aerial triangulation accuracy, ground control point accuracy, lidar-relative swath-to-swath precision and recommended minimum Nominal Pulse Density (NPD), horizontal accuracy of elevation data, delineation of low confidence areas for vertical data, and the required spatial distribution and number of checkpoints based on project area. Edition 2 introduces major changes to Edition 1 of the Standards. The changes summarized in the Foreword were made based on the feedback received from the users of the Standards, the state of sensors technologies, and the current industry requirements.

1.1 Scope and Applicability

These Standards are intended to be broadly based, technology independent, and applicable to most common mapping applications and projects. Specifically, these Standards are to be used by geospatial data producers and data users to determine the positional accuracy requirements for final geospatial products; it does not, however, address classification accuracy for thematic maps.

New to this edition, these Standards provide best practices and guidelines recommended to meet the accuracy thresholds stated herein. Detailed testing methodologies are specified, as are key elements to be considered in data acquisition and processing for products intended to meet these Standards. However, it is ultimately the responsibility of the data producer to set forth project design parameters, processing steps, and quality control procedures to ensure all data and derived products meet specified project accuracy requirements.

1.2 Limitations

Edition 2 of these Standards addresses accuracy thresholds and testing methodologies achievable with current technology. It also addresses shortcomings in Edition 1, as indicated by users of the Standards over the decade following the first edition's publication.

Additional accuracy assessment needs identified by the Working Group but not addressed in Edition 2 include:

- Positional accuracy of linear features (as opposed to well-defined points).
- Rigorous total propagated uncertainty (TPU) error modeling.
- Robust statistics for data sets that do not meet the criteria for normally-distributed error.
- Image quality factors, such as edge definition, color balance, and contrast.

- Robust assessment of the distribution and density of ground control points and checkpoints.

These Standards are intended to be a living document which can be updated in future editions to reflect changing technologies and user needs. As stated in the Foreword, Edition 2 includes five Addenda on general and best practices and guidelines. Subject matter experts are encouraged to develop and submit additional Addenda to ASPRS for review and publication.

To date, these Standards do not reference existing international Standards. These references could be considered as part of a future edition.

1.3 Structure and Format

Primary terms and definitions, references, and requirements are stated within the main body of the Standards (Sections 1 through 7).

Detailed supporting background information and accuracy conversion examples are given in Appendices A through D:

- Appendix A provides a background summary of other Standards, specifications, and guidelines that are relevant to ASPRS but which do not satisfy current requirements for digital geospatial data.
- Appendix B provides accuracy/quality examples and overall guidelines for implementing the Standards.
- Appendix C provides guidelines for accuracy testing and reporting.
- Appendix D provides examples on computing product accuracy according to Edition 2 of these Standards.

Addenda I through V present best practices and guidelines in the following areas of practice:

- Addendum I: General Best Practices and Guidelines
- Addendum II: Best Practices and Guidelines for Field Surveying for Ground Control and Checkpoints
- Addendum III: Best Practices and Guidelines for Mapping with Photogrammetry
- Addendum IV: Best Practices and Guidelines for Mapping with Lidar
- Addendum V: Best Practices and Guidelines for Mapping with UAS

2. CONFORMANCE

No conformance requirements are established for these Standards.

3. REFERENCES

American Society for Photogrammetry and Remote Sensing (ASPRS), 2014. ASPRS Positional Accuracy Standards for Digital Geospatial Data, URL: *https://publicdocuments.asprs.org/2014-PositionalAccuracyStd*.

American Society for Photogrammetry and Remote Sensing (ASPRS), 1990. ASPRS Accuracy Standards for Large-Scale Maps, URL: *https://publicdocuments.asprs.org/1990-AccuracyStandard*.

American Society for Photogrammetry and Remote Sensing (ASPRS), 2004. ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data, URL: *https://publicdocuments.asprs.org/2004-LidarVerticalAccuracy*.

Bureau of the Budget, 1947. United States National Map Accuracy Standards, URL: *https://publicdocuments.asprs.org/1947-NMAS*.

Dieck, R.H., 2007. *Measurement uncertainty: methods and applications*, Instrument Society of America, Research Triangle Park, North Carolina, 277 pp.

Federal Geographic Data Committee, 1998. FGDC-STD-007.2-1998, Geospatial Positioning Accuracy Standards, Part 2: Standards for Geodetic Networks, FGDC, c/o U.S. Geological Survey, URL: *https://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2*.

Federal Geographic Data Committee, 1998. FGDC-STD-007.3-1998, Geospatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy (NSSDA), FGDC, c/o U.S. Geological Survey, URL: *https://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3.*

LibreTexts Statistics Library, URL: *https://stats.libretexts.org/*

National Digital Elevation Program (NDEP), 2004. *NDEP Guidelines for Digital Elevation Data*, URL: *https://publicdocuments.asprs.org/2004-NDEPGuidelines*.

National Geodetic Survey (NGS), 1997. NOAA Technical Memorandum NOS NGS-58, Version 4.3: Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm), URL: *https://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html*.

National Geodetic Survey (NGS), 2008. NOAA Technical Memorandum NOS NGS-59, Version 1.5: Guidelines for Establishing GPS-Derived Orthometric Heights, URL: *http://www.ngs.noaa.gov/PUBS_LIB/NGS592008069FINAL2.pdf*

Informative references for additional relevant guidelines and specifications are included in Appendix A.

4. AUTHORITY

The organization responsible for preparing, maintaining, and coordinating work on these Standards is the American Society for Photogrammetry and Remote Sensing (ASPRS). The Working Group on Positional Accuracy Standards was formed under the auspices of the ASPRS Standards Committee to consider user feedback and author revisions appearing in Edition 2. For further information, contact the ASPRS Standards Committee at *standardscommittee@asprs.org*.

5. TERMS AND DEFINITIONS

- *absolute accuracy* – A measure that accounts for all systematic and random positional errors in a data set when the data set is referenced to a known and explicitly-specified datum.

- *accuracy* – The closeness of an estimated value (measured or computed, for example) to a standard or accepted (true) value of a particular quantity together with an explicit reference to the specific standard or accepted value. Not to be confused with *precision*.
- *accuracy class* (horizontal, vertical, and three-dimensional positional accuracy classes) – The quantification of a quality threshold in a project's scope of work. Accuracy class is expressed in this and previous Editions of the Standards as a function of the mapping product's RMSE.
- *product accuracy* – Actual achieved accuracy (horizontal, vertical, and three-dimensional positional accuracy) computed by statistical means for a geospatial dataset.
- *target accuracy* – Intended accuracy (horizontal, vertical, and three-dimensional positional accuracy) of the final product.
- *bias* – A systematic error inherent in measurements, due to some deficiency in the measurement process or subsequent processing. Biases can be detected, quantified, and removed if a correct procedure is followed. Biases should be removed from a data set before accuracy assessment is performed.
- *blunder* – A mistake resulting from carelessness or negligence. Not to be confused with *error*; refer to positional error below for more information.
- *confidence level* – The percentage of points within a data set that are estimated to meet the stated accuracy; e.g., accuracy reported at the 95% confidence level means that 95% of the positions in the data set will have an error with respect to true ground position that are less than the reported accuracy value.
- *data internal precision* (formerly, relative accuracy) – A measure of the variation of positional accuracy from point to point within a data set when evaluated across a leveled plane. In these Standards, it relates to the vertical quality of elevation data.
- *ground sample distance (GSD)* – The linear dimension of a sample pixel’s footprint on the ground. In raw imagery, pixel size is not uniform and varies based on sensor orientation and terrain. The term “nominal GSD” refers to the average or approximate size of pixels in raw imagery. In orthorectified imagery, the GSD for all pixels is uniform and constant regardless of the terrain variation.
- *horizontal accuracy* – The horizontal (radial) component of positional error in a data set with respect to a horizontal datum at a specified confidence level. The horizontal accuracy is computed from the horizontal positional error along the X and Y axes using the following formula:

$$RMSE_H = \sqrt{{RMSE_X}^2 + {RMSE_Y}^2}$$

- *inertial measurement unit (IMU)* – A combination of multiple accelerometers and gyroscopes used to measure absolute spatial displacement. In geospatial sensors technologies, the IMU is mainly used to measure sensor orientation angles, roll, pitch, and heading.

- *mean error* – The average positional error in a set of values for one dimension (X, Y, or Z), obtained by adding all errors in a single dimension together and then dividing by the total number of errors for that dimension.
- *network accuracy* – The uncertainty in the coordinates of mapped points with respect to the geodetic datum at the specified confidence level. In other words, network accuracy measures how well coordinates approach an ideal, error-free datum.
- *non-vegetated vertical accuracy (NVA)* – the vertical accuracy of the elevation surface in open terrain or bare earth.
- *percentile* – A measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall. For example, the 95th percentile is the value (or score) below which 95 percent of the observations may be found. For accuracy testing, percentile calculations are based on the absolute values of the errors, since it is the magnitude of the errors and not the sign that is of concern.
- *positional error* – The difference between data set coordinate values and coordinate values from an independent source of higher accuracy for identical points. Positional error is measured along each of the three coordinates axes: X, Y, and Z. It should be noted that this is a somewhat loose usage of the term “error,” which, formally, is the difference between the measured or computed value of a quantity and its true value. Since the true values of spatial coordinates can never be known, true errors can never be known. The values referred to as “errors” throughout these Standards are more formally known as “residuals.”
- *precision* – The closeness with which measurements agree with each other. Please note that, unlike RMSE, precision does not show the systematic error, or bias, if it is present in the measurements.
- *resolution* – The degree of fineness to which a measurement can be made. For example, the smallest unit a sensor can detect or the smallest unit an orthoimage depicts.
- *root-mean-square error (RMSE)* – The square root of the average of the set of squared differences between data set coordinate values and coordinate values from an independent source of higher accuracy for identical points.
- *skew* – A measure of the asymmetry of a probability distribution. Skewness values can be positive, zero, or negative within a data set. A skewness value near zero does not always imply that the distribution is symmetrical; however, a symmetrical distribution will always have a skew of, or close to, zero.
- *standard deviation* – A measure of spread or dispersion of a sample of errors around the sample mean error. It is a measure of precision, rather than accuracy; the standard deviation does not account for uncorrected systematic errors.
- *systematic error* – An error whose algebraic sign and, to some extent, magnitude bears a fixed relation to some condition or set of conditions. Systematic errors follow some fixed pattern and are introduced by data collection procedures, data processing, or a given datum.

- *three-dimensional positional accuracy* – The accuracy of the three-dimensional position (X, Y, and Z) of features with respect to horizontal and vertical datums as computed using the following formula:

$$RMSE_{3D} = \sqrt{{RMSE_X}^2 + {RMSE_Y}^2 + {RMSE_Z}^2}$$

- *uncertainty (of measurement)* – a parameter that characterizes the dispersion of measured values, or the range in which the "true" value most likely lies. Alternately, an estimate of the limits of the error in a measurement (where "error" is defined as the difference between the theoretically-unknowable "true" value of a parameter and its measured value). Standard uncertainty refers to uncertainty expressed as a standard deviation.

- *vegetated vertical accuracy (VVA)* – accuracy of the elevation surface in areas where terrain is covered by vegetation.

- *vertical accuracy* – The vertical component of the positional accuracy of a data set with respect to a vertical datum, at a specified confidence level. The vertical accuracy is computed from the vertical positional error along the Z axis. Vertical accuracy is presented as $RMSE_V$. For point cloud data—whether it be from lidar, IFSAR, or photogrammetry—vertical accuracy is typically taken as a point-to-surface measurement from the checkpoint normal to the point cloud surface.

For additional terms and more comprehensive definitions, refer to Glossary of Mapping Sciences (1994); Manual of Airborne Topographic Lidar (2012); Manual of Photogrammetry, 6th Edition (2013); and Digital Elevation Model Technologies and Applications: The DEM User's Manual, 3rd Edition (2018)—all published by ASPRS.

6. SYMBOLS, ABBREVIATED TERMS, AND NOTATIONS

- ASPRS - American Society for Photogrammetry and Remote Sensing
- DEM - Digital Elevation Model
- DTM - Digital Terrain Model
- GCP - Ground Control Point
- GSD - Ground Sample Distance
- GNSS - Global Navigation Satellite System
- GPS - Global Positioning System
- IDW - Inverse Distance Weighing
- IFSAR - Interferometric Synthetic Aperture Radar
- IMU - Inertial Measurement Unit
- NGPS - Nominal Ground Point Spacing
- NPD - Nominal Pulse Density

- NMAS - National Map Accuracy Standards
- NPS - Nominal Pulse Spacing
- NSSDA - National Standard for Spatial Data Accuracy
- NVA - Non-Vegetated Vertical Accuracy
- RMSE - Root Mean Square Error
    - $RMSE_{3D}$ - the three-dimensional RMSE that represents both horizontal and vertical errors in a point position
    - RMS_{DZ} – the RMSE of differences in elevations sampled at the same point location in overlapping swaths of lidar data
    - $RMSE_H$ - the horizontal linear RMSE in the radial direction that includes both x- and y-coordinate errors
    - $RMSE_V$ - vertical linear RMSE that represents the vertical accuracy of elevation data
    - $RMSE_X$ - linear RMSE in the X direction (Easting)
    - $RMSE_Y$ - linear RMSE in the Y direction (Northing)
    - $RMSE_Z$ - linear RMSE in the Z direction (Elevation)
- TIN - Triangulated Irregular Network
- VVA - Vegetated Vertical Accuracy
- $\overline{x}$ - sample mean error
- σ - sample standard deviation
- γ_1 - sample skewness

7. SPECIFIC REQUIREMENTS

These Standards define accuracy classes based on RMSE thresholds for digital orthoimagery, digital planimetric data, and digital elevation data.

Accuracy testing is always recommended but may not be required for all data sets; specific requirements must be addressed in the project specifications. When testing is required:

- Horizontal accuracy shall be tested by comparing the planimetric coordinates of well-defined points in the data set with coordinates determined from an independent source of higher accuracy.
- Vertical accuracy shall be tested by comparing the elevations of the surface represented by the data set with elevations determined from an independent source of higher accuracy. This is done by comparing the elevations of the checkpoints with elevations interpolated from the data set at the same X, Y coordinates. See Section C.11 for detailed guidance on interpolation methods.

- Three-dimensional accuracy shall be tested by comparing the X, Y, and Z coordinates of well-defined points in the data set with X, Y, and Z coordinates determined from an independent source of higher accuracy.

All accuracies are assumed to be relative to the published datum as specified in the project specifications. Ground control accuracies and survey procedures should be established according to project requirements. Unless specified to the contrary, it is expected that all ground control and checkpoints should follow guidelines for network accuracy as detailed in the Geospatial Positioning Accuracy Standards, Part 2: Standards for Geodetic Networks (FGDC-STD-007.2-1998), the NOAA Technical Memorandum NOS NGS 92, and Addendum II of these Standards. When local control is needed to meet specific accuracies or project needs, it must be clearly identified in both the project specifications and the metadata. When reporting accuracy, the number of significant digits in the reported accuracy values shall be equal to the number of significant digits in the delivered product coordinates.

7.1 Statistical Assessment of Accuracy

Horizontal accuracy is to be expressed as $RMSE_H$, derived from two horizontal error components, $RMSE_X$ and $RMSE_Y$(see Section 7.3). Vertical accuracy is to be expressed as $RMSE_V$ (see Section 7.4). Three-dimensional positional accuracy is to be expressed as $RMSE_{3D}$, derived from horizontal and vertical accuracy component, $RMSE_H$ and $RMSE_V$ (see Section 7.5). Furthermore, elevation data sets shall also be assessed for horizontal accuracy ($RMSE_H$) whenever possible (see Section 7.6).

More details on the application and calculation of these statistics can be found in Appendix D - Accuracy Statistics and Examples.

7.2 Systematic Error and Mean Error Assumptions

Except for vertical data in vegetated terrain, the assessment methods outlined in these Standards assume that the data set errors are normally distributed and that any significant systematic errors or biases have been removed. It is the responsibility of the data producer to test and verify that the data meets this requirement by evaluating all statistical parameters—including standard deviation, median, mean, and RMSE—as they may aid in the discovery and diagnosis of systematic errors. Evaluation of additional statistical measures, such as kurtosis and skew, are strongly advised.

Acceptable mean error may vary by project and should be negotiated between the data producer and the client. As a rule, these Standards recommend that the mean error be less than 25% of the target RMSE specified for the project. Mean error greater than 25% of the target RMSE, whether identified pre-delivery or post-delivery, should be investigated to diagnose the cause. These findings should then be reported in the metadata. If further action is taken to correct bias and reduce the mean error, this action should also be reported in the metadata. If the data producer and client agree to accept a mean error greater than 25% of the RMSE, this should be reported in the metadata as well.

When RMSE testing is performed, a discrepancy between the data set and a checkpoint that exceeds three times the target RMSE threshold in any component of the coordinate (X, Y, or Z) shall be interpreted as a blunder. The blunder should be investigated, explained, and corrected before the data set is considered to meet these Standards. Blunders may not be discarded without proper investigation. Removal of blunders should be explained and reported in the project metadata.

7.3 Horizontal Positional Accuracy Standard for Geospatial Data

Table 7.1 defines the primary horizontal accuracy standard for digital data, including digital orthoimagery, digital planimetric data, scaled planimetric maps, and elevation data. These Standards specify horizontal accuracy classes in terms of $RMSE_H$, the combined linear error along a horizontal plane in the radial direction. $RMSE_H$ is derived from $RMSE_X$ and $RMSE_Y$ according to the following formula:

$$RMSE_H = \sqrt{RMSE_X{}^2 + RMSE_Y{}^2}$$

Former ASPRS Standards used discrete, numerically-ranked accuracy classes tied to map scale (i.e., Class 1, Class 2, Class 3). Many modern applications of geospatial data call for horizontal accuracies that are not tied directly to compilation scale, resolution of the source imagery, or final pixel resolution (GSD). Therefore, these Standards allow more flexibility; they do not classify horizontal accuracy discretely, nor do they tie accuracy class to map scale.

According to these Standards, horizontal accuracy needs should be determined by project requirements, and the horizontal accuracy class of a data set should be expressed as a function of $RMSE_H$. For example, a project's scope of work could call for digital orthoimagery, digital planimetric data, or scaled maps produced to meet the ASPRS Positional Accuracy Standards for 7.5-cm Horizontal Accuracy Class, meaning that the $RMSE_H$ for the resulting data set must be ≤ 7.5 cm.

In the case of digital orthoimagery mosaics, an additional criterion for the allowable mismatch at seamlines of ≤ 2* $RMSE_H$ is specified in Table 7.1. It should be understood that the term $RMSE_H$ should be computed using both $\mathrm{RMSE}_{\mathrm{H}_1}$ and $\mathrm{RMSE}_{\mathrm{H}_2}$ error components, as described in section 7.11.3.

Table 7.1 Horizontal Accuracy Classes for Geospatial Data

Horizontal Accuracy Class	Absolute Accuracy $RMSE_H$ (cm)	Orthoimagery Mosaic Seamline Mismatch (cm)
#-cm	*≤ #*	*≤ 2*#*

Appendix B includes examples that relate accuracy classes as defined in these Standards to equivalent classes in legacy Standards. Table B.4 provides $RMSE_H$ recommendations for digital orthoimagery of various pixel sizes. Table B.4 also relates Horizontal Accuracy Class and $RMSE_H$ of digital planimetric data to legacy ASPRS and NMAS Standards. The recommended associations of $RMSE_H$ and GSD presented in Table B.4 are intended to guide users through the transition from legacy to modern Standards. Such associations may change in the future as mapping technologies continue to advance and evolve. These Standards do not endorse the use of GSD, map scale, or contour interval to express product accuracy.

7.4 Vertical Positional Accuracy Standard for Elevation Data

Vertical accuracy is to be expressed as $RMSE_V$ in both vegetated and non-vegetated terrain. Vertical Accuracy Classes are defined by the associated $RMSE_V$ specified for the product. It should be understood that the term $RMSE_V$ should be computed using both $RMSE_{V_1}$ and $RMSE_{V_2}$ error components as described in section 7.11.4. While the Non-Vegetated Vertical Accuracy (NVA) must meet accuracy thresholds listed in Table 7.2, the Vegetated Vertical Accuracy (VVA) has no pass/fail criteria and needs only to be tested and reported as found. If the NVA meets user specifications, VVA should be accepted at the reported accuracy level.

For projects where vegetated terrain is dominant, the data producer and the client may agree on an acceptable threshold for the VVA. Table 7.2 provides the Vertical Accuracy Class specifications for digital elevation data, including Data Internal Precision requirements where applicable, such as in lidar acquisition. Horizontal accuracy of elevation data should also be explicitly specified and reported, as discussed in Section 7.6.

Table 7.2 Vertical Accuracy Classes for Digital Elevation Data

Vertical Accuracy Class	Absolute Accuracy		Data Internal Precision (where applicable)		
	NVA $RMSE_V$ (cm)	VVA $RMSE_V$ (cm)	Within-Swath Smooth Surface Precision Max Diff (cm)	Swath-to-Swath Non-Vegetated RMS_{DZ} (cm)	Swath-to-Swath Non-Vegetated Max Diff (cm)
#-cm	*≤ #*	*As found*	*≤ 0.60*#*	*≤ 0.80*#*	*≤ 1.60*#*

Table B.5 lists ten typical examples of Vertical Accuracy Class, $RMSE_V$, and corresponding Data Internal Precision values based on the equations shown in Table 7.2 above. Table B.6 relates Vertical Accuracy Class and $RMSE_V$ of digital elevation data to legacy ASPRS and NMAS Standards for the same examples.

The degree to which an elevation surface accurately represents terrain is not only represented by vertical agreement at ground checkpoints; accurate representation of terrain is also a function of point spacing/density. It is possible to have a very small $RMSE_V$ relative to checkpoints, even when the surface lacks sufficient resolution to represent details present in the terrain (for more on the subject, refer to Addendum I of these Standards). Table B.7 provides recommended minimum point density and point spacing at typical Vertical Accuracy Classes.

NVA should be computed based on ground checkpoints located in traditional open (bare soil, sand, gravel, and short grass) and urban (asphalt and concrete) terrain surfaces. VVA is computed based on ground checkpoints in all types of vegetated terrain, including tall weeds, crop land, brush, and fully-forested areas. VVA is exempted from pass/fail testing criteria, and only needs to be tested according to the requirements set forth in these Standards. The results should then be reported in the metadata.

7.5 Three-Dimensional Positional Accuracy Standard for Geospatial Data

Table 7.3 defines the three-dimensional accuracy standard for any three-dimensional digital data as a combination of horizontal and vertical radial error. $RMSE_{3D}$ is derived from the horizontal and vertical components of error according to the following formula:

$$RMSE_{3D} = \sqrt{RMSE_X{}^2 + RMSE_Y{}^2 + RMSE_Z{}^2} \text{ or,}$$

$$RMSE_{3D} = \sqrt{RMSE_H{}^2 + RMSE_V{}^2}$$

Three-dimensional positional accuracy can be computed for any type of geospatial data, as long as the horizontal and vertical positional accuracy are assessed and reported as described in Sections 7.3 and 7.4 above. Colorized point clouds and digital twins are good candidates for three-dimensional positional accuracy assessment.

Table 7.3 Three-Dimensional Accuracy Classes for Geospatial Data

3D Accuracy Class	Absolute Accuracy
	$RMSE_{3D}$ (cm)
#-cm	≤ #

7.6 Horizontal Accuracy of Elevation Data

These Standards outline horizontal accuracy testing requirements for elevation data created from stereo photogrammetry and lidar. For other technologies, appropriate horizontal accuracies for elevation data should be negotiated between the data producer and the client, with specific accuracy thresholds and methods based on the technology used and the project design. In these cases, the data producer assumes responsibility for establishing appropriate parameters for data acquisition and testing to verify that horizontal accuracies meet the stated project requirements. Guidelines for testing the horizontal accuracy of elevation data sets are set forth in Section C.6.

Photogrammetric elevation data: For elevation data derived using stereo photogrammetry, apply the same Horizontal Accuracy Class that would be used for planimetric data or digital orthoimagery produced from the same source, based on the same photogrammetric adjustment. Horizontal accuracies, either “produced to meet” or “tested to meet,” should be reported for all photogrammetrically derived elevation data sets, expressed as $RMSE_H$.

Lidar elevation data: Horizontal error in lidar-derived elevation data is largely a function of the following and can be estimated based on related parameters:

- sensor positioning error as derived from the Global Navigation Satellite System (GNSS)
- attitude (angular orientation) error as derived from the IMU
- flying height above the mean terrain

The following equation[1] provides an estimate for the horizontal accuracy for a lidar-derived data set ($RMSE_H$), assuming positional accuracy of the GNSS; roll, pitch, and heading accuracy of the Inertial Measurement Unit (IMU); and the flying height are quantified:

[1]The method presented here is one approach; there are other methods for estimating the horizontal accuracy of lidar data sets, which are not presented herein. Abdullah, Q., 2014, unpublished data.

$$RMSE_H = \sqrt{(GNSS\ positional\ error)^2 + \left(\frac{tan\ (IMU\ roll\ or\ pitch\ error) +\ tan\ (IMU\ heading\ error)}{1.478} * \ flying\ height\right)^2}$$

where:

- flying height above mean terrain is in meters (m),
- GNSS positional errors are radial, in centimeters (cm) and can be derived from published manufacturer specifications,
- and IMU errors are in angular units and can be derived from published manufacturer specifications.

For most lidar systems used in mapping applications, other error sources, such as laser ranging and clock timing, are small contributors to the error budget and can be considered negligible when estimating horizontal error. It is worth mentioning here that lidar beam divergence, or the spread of the pulse footprint, was not factored in the previous equation because 1) most lidar systems used by the industry today have very narrow footprints, and 2) the beam divergence is sensitive to the terrain slope and the varying footprint across the field of view of the sensor, and attempting to factor it in to the calculation would add a new level of complexity to the computations.

If the desired horizontal accuracy class for the lidar data has been agreed upon by the data producer and client, then the equation above can be rearranged to solve for the recommended flying height above mean terrain (FH):

$$FH = \frac{1.478}{tan(IMU\ roll\ or\ pitch\ error) +\ tan(IMU\ heading\ error)} \sqrt{{RMSE_H}^2 - (GNSS\ positional\ error)^2}$$

Table B.8 expresses estimates of horizontal error ($RMSE_H$) as a function of flying height using an example set of GNSS and IMU errors defined in Section B.8.

7.7 Low Confidence Areas in Elevation Data

In areas of dense vegetation, it can be difficult to collect reliable elevation data. This occurs in imagery where the ground is obscured or in deep shadow, or with lidar or radar imaging where there is poor signal penetration. These Standards recommend that such low confidence areas be delineated by polygons and reported in the metadata. Low confidence polygons are the digital equivalent to the dashed contours referred to in legacy Standards. The thoroughness of such delineation should be discussed and agreed upon by the data user and data producer according to project requirements.

Section C.8 provides specific guidelines for collecting and reporting low confidence areas in elevation data.

7.8 Accuracy Requirements for Aerial Triangulation and IMU-Based Sensor Orientation

The quality and accuracy of the aerial triangulation (if performed) and/or the GNSS/IMU-based direct georeferencing play a key role in determining the final accuracy of imagery-derived mapping products.

For photogrammetric data sets, the accuracy of aerial triangulation and/or the GNSS/IMU-based direct georeferencing must be higher than the accuracy of the derived products. The accuracy of the aerial triangulation should be of the same order as the accuracy of the ground control used for the aerial triangulation, as explained in Section 7.9 below.

For GNSS/IMU-based direct georeferencing, orientation accuracy shall be evaluated by comparing coordinates of checkpoints read from the imagery (using stereo photogrammetric measurements or other appropriate methods) to coordinates of the checkpoints as determined from higher-accuracy source data.

Aerial triangulation accuracies shall be evaluated using one of the following methods:

- Comparing coordinates of checkpoints computed in the aerial triangulation solution to coordinates of the checkpoints as determined from higher-accuracy source data.
- Comparing coordinates read from the imagery (using stereo photogrammetric measurements or other appropriate method) to coordinates of the checkpoints as determined from higher-accuracy source data.

For projects providing deliverables that are only required to meet horizontal accuracy (orthoimagery or two-dimensional vector data), aerial triangulation errors in Z have a smaller impact on the horizontal error budget than errors in X and Y. In such cases, the aerial triangulation requirements for $RMSE_V$ can be relaxed. For this reason, these Standards recognize two different criteria for aerial triangulation accuracy:

- Aerial triangulation designed for digital planimetric data (orthoimagery and/or map) only:
  - $\mathrm{RMSE}_{\mathrm{H}_{1(\mathrm{AT})}} \leq ½ * \mathrm{RMSE}_{\mathrm{H}_{(\mathrm{MAP})}}$
  - $\mathrm{RMSE}_{\mathrm{V}_{1(\mathrm{AT})}} \leq \mathrm{RMSE}_{\mathrm{H}_{(\mathrm{MAP})}}$

Note: The exact contribution of aerial triangulation errors in Z to the overall horizontal error budget for the end products depends on ground point location in the image and other factors. Achieving $\mathrm{RMSE}_{\mathrm{V}_{(\mathrm{AT})}}$ less than or equal to target $RMSE_H$ for the final product requires a stringent workflow to control the various source of deformations within the process caused by imagery and camera parameters and other factors that typically impact the horizontal error budget.

- Aerial triangulation designed for projects that include elevation or 3D products, in addition to digital planimetric data (orthoimagery and/or map):
  - $\mathrm{RMSE}_{\mathrm{H}_{1(\mathrm{AT})}} \leq ½ * \mathrm{RMSE}_{\mathrm{H}_{(\mathrm{MAP})}}$
  - $\mathrm{RMSE}_{\mathrm{V}_{1(\mathrm{AT})}} \leq ½ * \mathrm{RMSE}_{\mathrm{V}_{(\mathrm{DEM})}}$

In the creation of any photogrammetric product, it is strongly recommended that the results of aerial triangulation be scrutinized for accuracy. In the event aerial triangulation results do not meet the criteria stated above but do meet the RMSE requirements of the final product, attention should be shifted to the accuracy of the final products. If the final products meet target accuracies, an agreement to accept the aerial triangulation results should be made between the data producer and client. This should then be reported in the project metadata.

Section B.1 provides examples of practical applications of aerial triangulation accuracy requirements.

7.9 Accuracy Requirements for Ground Control Used for Aerial Triangulation

The accuracy of the ground control points should be twice the target accuracy of the final products, according to the following two categories:

- Ground control for aerial triangulation designed for digital planimetric data (orthoimagery and/or map) only:
    - $\mathrm{RMSE}_{\mathrm{H}_{(\mathrm{GCP})}} \leq ½ * \mathrm{RMSE}_{\mathrm{H}_{(\mathrm{MAP})}}$
    - $\mathrm{RMSE}_{\mathrm{V}_{(\mathrm{GCP})}} \leq \mathrm{RMSE}_{\mathrm{H}_{(\mathrm{MAP})}}$
- Ground control for aerial triangulation designed for projects that include elevation or 3D products, in addition to digital planimetric data (orthoimagery and/or map):
    - $\mathrm{RMSE}_{\mathrm{H}_{(\mathrm{GCP})}} \leq ½ * \mathrm{RMSE}_{\mathrm{V}_{(\mathrm{MAP})}}$
    - $\mathrm{RMSE}_{\mathrm{V}_{(\mathrm{GCP})}} \leq ½ * \mathrm{RMSE}_{\mathrm{V}_{(\mathrm{DEM})}}$

Section B.1 provides examples of the practical application of ground control accuracy requirements for aerial triangulation.

7.10 Accuracy Requirements for Ground Control Used for Lidar

The accuracy of the ground control points used for lidar calibration and boresighting should be twice the target accuracy of the final products. Similarly, ground checkpoints used to assess lidar data accuracy should be twice the target accuracy of the final products.

- $\mathrm{RMSE}_{\mathrm{V}_{(\mathrm{GCP})}} \leq ½ * \mathrm{RMSE}_{\mathrm{V}_{(\mathrm{DEM})}}$

Similar guidelines can be followed for other digital data acquisition technologies, such as IFSAR.

7.11 Positional Accuracy Assessment of Geospatial Data Products

Geospatial data exchanged among users should be accompanied by metadata clearly stating positional accuracy (as defined in this or an equivalent Standard), as positional accuracy is an important consideration in determining applicability of the data for an intended purpose. Mislabeled or poorly-reported positional accuracy can result in catastrophic consequences.

Assessment of product accuracy requires a network of checkpoints that is well distributed throughout the project area. This network should have higher positional accuracy than the product being tested. Ideally, checkpoints should be obtained using field surveying techniques as described in Addendum II, but it is also possible to obtain checkpoints from other sources if they meet the accuracy criteria defined herein. While assessing the horizontal accuracy of an orthometric or planimetric map is straightforward, assessing vertical and three-dimensional accuracies need to be planned carefully. Vertical accuracy is computed from the vertical position error along the Z-axis. For point cloud data—whether it be from lidar, IFSAR, or photogrammetry—vertical accuracy is typically taken as a point-to-surface measurement from the checkpoint normal to the point cloud surface. Suitable surface generation methods such as TIN or IDW can be used for this accuracy assessment. Other surface modeling methods may be used as long as it is scientifically sound and accepted by the industry.

7.11.1 First Component of Positional Error – Product Fit to Checkpoints

For each checkpoint, the surveyed coordinates should be compared to the coordinates derived from the tested product. Then, the discrepancies between the two sets of coordinates should be computed and tabulated. The product fit to checkpoints is represented by the first component of error, $\mathrm{RMSE}_{\mathrm{H}_1}$, $\mathrm{RMSE}_{\mathrm{V}_1}$, or $\mathrm{RMSE}_{\mathrm{3D}_1}$. RMSE should be computed in each dimension from all the individual computed discrepancies between the product and the checkpoints or control points in that dimension, as stated in the following formula:

$$RMSE_X = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{i(map)} - x_{i(surveyed)})^2}$$

$$RMSE_Y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{i(map)} - y_{i(surveyed)})^2}$$

$$RMSE_Z = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_{i(map)} - z_{i(surveyed)})^2}$$

The first component of horizontal error is:

$$RMSE_{H_1} = \sqrt{RMSE_X{}^2 + RMSE_Y{}^2}$$

The first component of vertical error is:

$$RMSE_{V_1} = RMSE_Z$$

The first component of three-dimensional error is:

$$RMSE_{3D_1} = \sqrt{RMSE_X{}^2 + RMSE_Y{}^2 + RMSE_Z{}^2}$$

7.11.2 Second Component of Positional Error – Survey Control and Checkpoint Error

The second component of positional error is the error of the survey of the control points and checkpoints[2]. Because these Standards have relaxed the requirement for survey point accuracy to two times the target product accuracy, as well as the high accuracy expected from the products, these errors can no longer be considered negligible.

The second component of positional error is represented as $\mathrm{RMSE}_{\mathrm{H}_2}$, $\mathrm{RMSE}_{\mathrm{V}_2}$, or $\mathrm{RMSE}_{\mathrm{3D}_2}$, and it is the quantity reported by the field surveyor.

[2] Abdullah, Q., "Rethinking Error Estimations in Geospatial Data: The Correct Way to Determine Product Accuracy", PE&RS, July 2020

7.11.3 Horizontal Positional Accuracy

To compute the horizontal accuracy of a two-dimensional product, such as a planimetric map or orthorectified image, the height component of the survey point error is ignored. We assume that X (Easting) and Y (Northing) survey point errors are equal; that is, $\mathrm{RMSE}_{X_2} = \mathrm{RMSE}_{Y_2}$.

Using error propagation principles for Euclidean vectors:

$$Horizontal\ Product\ Accuracy\ (RMSE_H) = \sqrt{{RMSE_{H_1}}^2 + {RMSE_{H_2}}^2}$$

7.11.4 Vertical Positional Accuracy

Vertical product accuracy is computed from the first and second components of vertical error:

$$Vertical\ Product\ Accuracy\ (RMSE_V) = \sqrt{{RMSE_{V_1}}^2 + {RMSE_{V_2}}^2}$$

7.11.5 Three-dimensional Positional Accuracy

The three-dimensional product accuracy is computed from the vertical and horizontal product accuracy:

$$RMSE_{3D} = \sqrt{{RMSE_H}^2 + {RMSE_V}^2}$$

Table 7.4 provides examples of vertical product accuracy, assuming that the vertical survey point error reported by the surveyor is RMSE_{V_2} = 2.0-cm. Additional details can be found in Section C.6.

Table 7.4 Computing Vertical Product Accuracy

Fit to Checkpoints $\mathbf{RMSE}_{V_1}$ (cm)	Survey Checkpoint Accuracy $\mathbf{RMSE}_{V_2}$ (cm)	Vertical Product Accuracy $\mathbf{RMSE}_V$ (cm)
1.00	2.0	2.24
1.50	2.0	2.50
2.00	2.0	2.83
2.50	2.0	3.20
3.00	2.0	3.61
3.50	2.0	4.03
4.00	2.0	4.47
4.50	2.0	4.92
5.00	2.0	5.39
5.50	2.0	5.85
6.00	2.0	6.32
6.50	2.0	6.80
7.00	2.0	7.28
7.50	2.0	7.76
8.00	2.0	8.25
8.50	2.0	8.73
9.00	2.0	9.22
9.50	2.0	9.71
10.00	2.0	10.20

7.12 Checkpoint Accuracy and Placement

Pursuant to Edition 2 of the Standards, checkpoints used for product accuracy assessment shall be at least two times more accurate than the required accuracy of the geospatial product being evaluated. This shall hold true for survey checkpoints, as well as checkpoints derived from other geospatial data products. To avoid a biased accuracy assessment, a checkpoint should be located away from any ground control points used in the initial processing and data calibration.

Horizontal checkpoints shall be established at well-defined points. A well-defined point is a feature for which the horizontal position can be 1) placed with a high degree of certainty in the product being tested, and 2) measured to the required degree of accuracy with respect to the geodetic datum. Well-defined points must be easily visible or identifiable on the tested product and on the ground. In the case of orthorectified imagery, when rectifying the imagery, well-defined points shall not be selected on features that are above the elevation surface. For example, the corner of a building rooftop should not be used as a horizontal checkpoint in imagery that was orthorectified using a bare-earth DEM; however, if the imagery was orthorectified using a 3D model that includes buildings, then a point on a building rooftop may be an acceptable horizontal checkpoint.

Checkpoints used for vertical accuracy assessment shall be established at locations that minimize interpolation errors when comparing the product elevation surface to the elevations of the checkpoints. These checkpoints shall be surveyed in open terrain that is flat or in areas of gentle and uniform slope and it should not be placed near vertical artifacts or abrupt changes in elevation (preferably 3 meters or more away). Checkpoints used for vertical accuracy assessment are not required to meet the above requirements of well-defined points.

7.13 Checkpoint Density and Distribution

Checkpoints for accuracy assessment should be well distributed around the project area. Considerations made for challenging circumstances—such as rugged terrain, water bodies, heavy vegetation, and inaccessibility—are acceptable if agreed upon between the data producer and the client. In no case shall the assessment of planimetric accuracy of digital orthoimagery be based on fewer than thirty (30) checkpoints. Similarly, the assessment of the NVA or VVA of elevation data should be based on no fewer than thirty (30) checkpoints each. If either horizontal or vertical accuracy is assessed using fewer than thirty (30) checkpoints, a special reporting statement should be included, as outlined in section 7.15.1.

A quantitative methodology for characterization and specification of the spatial distribution of checkpoints that accounts for land cover type and project shape does not currently exist. Until such a methodology is developed and accepted, checkpoint density and distribution must be based on empirical results and simplified area-based methods.

Appendix C provides detailed guidelines and recommendations for checkpoint density and distribution. The requirements in Appendix C may be revised in the future as quantitative methods for determining the appropriate distribution of checkpoints are developed and approved.

7.14 Data Internal Precision (Relative Accuracy) of Lidar and IFSAR Data

Data internal precision assesses the internal geometric integrity of an elevation data set, without regard to survey control or absolute coordinates. These assessments can reveal potential systematic errors related to sensor stability, quality of GNSS trajectories, ranging precision, calibration of sensor models, and/or boresight alignment. Assessment of data internal precision includes two aspects of data quality: within-swath (smooth-surface) precision, and swath-to-swath precision. As stated in Table 7.2, requirements for data internal precision are more stringent than requirements for absolute accuracy.

Wherever the following assessment methods refer to raster surfaces created from lidar data, the raster cell size should be twice the nominal NPS of the lidar point cloud. Assessment of within-swath and swath-to-swath precision should be performed from these raster surfaces, using test areas in open, uniformly-sloping terrain that contain only single-return lidar points determined to be valid surface returns. Criteria for test areas are set forth in more detail in Section C.10.

7.14.1 Within-Swath (Smooth-Surface) Precision

Within-swath precision is usually only associated with lidar collections and is a measure of the precision of the system when detecting flat, hard surfaces. Within-swath internal precision is an indicator of ranging precision and sensor stability. Within-swath internal precision may be evaluated in single-swath data by creating two raster elevation surfaces—one from the minimum point elevation in each raster cell, and the other from the maximum point elevation in each raster cell. The two surfaces are differenced, and the maximum difference is compared to acceptable thresholds for each accuracy class as presented in Table 7.2.

Another method used to evaluate within-swath precision is to create two raster elevation surfaces—one using points with encoded scan direction flag = 0, and the other using points with encoded scan direction flag = 1. The two surfaces are then subtracted from each other to obtain the difference. There are no recommended quantitative thresholds, but this method of assessment can be helpful in revealing systematic errors in the data stemming from a hardware malfunction or a poorly-calibrated sensor model.

7.14.2 Swath-to-Swath Precision

Swath-to-swath precision for both lidar and IFSAR collections is measured in areas of open terrain within the swath overlap.

The first method of computing swath-to-swath precision is to create a surface from each of the overlapping swaths. An elevation is extracted from each surface at a number of point sample locations, then an elevation difference is calculated for each sample point. A root-mean-square difference, RMS_{DZ}, is then calculated from all the sample differences and compared to the threshold values presented in Table 7.2.

A second method of computing swath-to-swath precision is to create two raster elevation surfaces, one from each swath. The two surfaces are differenced, and an RMS_{DZ} calculated using sample areas that are in open terrain. This approach results in a more comprehensive assessment, and also provides the user with a visual representation of the swath-to-swath differences.

Section C.10 sets forth specific criteria for selecting checkpoint locations for swath-to-swath accuracy assessment.

7.15 Accuracy Reporting

Horizontal, vertical, and three-dimensional positional accuracies shall be assessed and formally reported according to their appropriate accuracy class, using one of the statements provided in sections 7.15.1 and 7.15.2 of these Standards.

In addition to accuracy class, related statistical quantities should be computed and reported, including:

- Residual errors at each checkpoint
- Maximum error
- Minimum error
- Mean error
- Median error
- Standard deviation
- RMSE

Product positional accuracy is reported according to one of the following scenarios:

7.15.1 Accuracy Reporting by Data User or Consultant

This type of reporting should only be based on a set of independent checkpoints. The positional accuracy of digital orthoimagery, planimetric data, and elevation data products shall be reported in the metadata in one of the manners listed below. For projects with NVA and VVA requirements, two three-dimensional positional accuracy values should be reported based on the use of NVA and VVA, respectively.

- Accuracy Testing Meets ASPRS Standard Requirements

  If testing is performed using a minimum of thirty (30) checkpoints, accuracy assessment results should be reported in the form of the following statements:

  - Reporting Horizontal Positional Accuracy

    "This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a __(cm) $RMSE_H$ horizontal positional accuracy class. The tested horizontal positional accuracy was found to be $RMSE_H$ = __(cm)".

  - Reporting Vertical Positional Accuracy

    "This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a __(cm) $RMSE_V$ Vertical Accuracy Class. NVA accuracy was found to be $RMSE_V$ = __(cm)." VVA accuracy was found to be $RMSE_V$ = __(cm)."

  - Reporting Three-Dimensional Positional Accuracy

"This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a ___ (cm) $RMSE_{3D}$ three-dimensional positional accuracy class. The tested three-dimensional accuracy was found to be $RMSE_{3D}$ = ___(cm)."

- Accuracy Testing Does Not Meet ASPRS Standard Requirements

  If testing is performed using fewer than thirty (30) checkpoints, accuracy assessment results should be reported in the form of the following statements:

  - Reporting Horizontal Positional Accuracy

    "This data set was tested as required by ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023). Although the Standards call for a minimum of thirty (30) checkpoints, this test was performed using ONLY __ checkpoints. This data set was produced to meet a ___(cm) $RMSE_H$ horizontal positional accuracy class. The tested horizontal positional accuracy was found to be $RMSE_H$ = ___(cm) using the reduced number of checkpoints."

  - Reporting Vertical Positional Accuracy

    "This data set was tested as required by ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023). Although the Standards call for a minimum of thirty (30) checkpoints, this test was performed using ONLY __ checkpoints. This data set was produced to meet a ___(cm) $RMSE_V$ vertical positional accuracy class. The tested vertical positional accuracy was found to be $RMSE_V$ = ___(cm) using the reduced number of checkpoints."

  - Reporting Three-Dimensional Positional Accuracy

    "This data set was tested as required by ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023). Although the Standards call for a minimum of thirty (30) checkpoints, this test was performed using ONLY __ checkpoints. This data set was produced to meet a ___(cm) $RMSE_{3D}$ three-dimensional positional accuracy class. The tested three-dimensional positional accuracy was found to be $RMSE_{3D}$ = ___(cm) using the reduced number of checkpoints."

7.15.2 Accuracy Reporting by Data Producer

In most cases, data producers do not have access to independent checkpoints to assess product accuracy. If rigorous testing is not performed by the data producer due to the absence of independent checkpoints, accuracy statements should specify that the data was "produced to meet" a stated accuracy. This "produced to meet'' statement is equivalent to the "compiled to meet" statement used by prior Standards when referring to cartographic maps. The "produced to meet'' statement is appropriate for data producers who employ mature technologies, and who follow best practices and guidelines through established and documented procedures during project design, data processing and quality control, as set forth in the Addenda to these Standards. However, if enough independent checkpoints are available to the data producer to assess product accuracy, it will do no harm to report the accuracy using the statement provided in section 7.15.1 above.

If not enough checkpoints are available, but the data producer has demonstrated that they are able to produce repeatable, reliable results and thus able to guarantee the produced-to-meet accuracy, they may report product accuracy in the form of the following statements:

- Reporting Horizontal Positional Accuracy

  "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a __(cm) $RMSE_H$ horizontal positional accuracy class.

- Reporting Vertical Positional Accuracy

  "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a __(cm) $RMSE_V$ vertical accuracy class.

- Reporting Three-Dimensional Positional Accuracy

  "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2 (2023) for a ___ (cm) $RMSE_{3D}$ three-dimensional positional accuracy class.

APPENDIX A — BACKGROUND AND JUSTIFICATIONS (INFORMATIVE)

A.1 Legacy Standards and Guidelines

Accuracy standards for geospatial data have broad applications both nationally and internationally. Besides assuring that data accuracy needs are met, it also establishes quality and performance specifications for the different geospatial products and processes, including: software and data processing, datum and coordinates systems, hardware and sensor performance, and auxiliary systems. Specifications have a much narrower focus: they determine what technical requirements and acceptance criteria a geospatial product must conform to in order to be considered acceptable for a specific, set purpose. Guidelines, on the other hand, provide recommendations for acquiring, processing, and analyzing geospatial data, and are normally intended to promote consistency and best practices in the industry.

The following is a summary of standards, specifications, and guidelines relevant to ASPRS but which do not fully satisfy current requirements for accuracy standards for digital geospatial data:

- The *National Map Accuracy Standards* (NMAS) of 1947 established horizontal accuracy thresholds for the *Circular Map Accuracy Standard* (CMAS) as a function of map scale, and vertical accuracy thresholds for the *Vertical Map Accuracy Standard* (VMAS) as a function of contour interval—both reported at the 90% confidence level. Because NMAS accuracy thresholds are a function of the map scale and/or contour interval of a printed map, they are inappropriate for digital geospatial data where scale and contour interval are changed with a push of a button without altering the underlying horizontal and/or vertical accuracy.
- The *ASPRS 1990 Accuracy Standards for Large-Scale Maps* established horizontal and vertical accuracy thresholds in terms of RMSE values in X, Y, and Z at ground scale. However, because the RMSE thresholds for Class 1, Class 2, and Class 3 products pertain to printed maps with published map scales and contour intervals, these ASPRS Standards are similarly inappropriate for digital geospatial data.
- The *National Standard for Spatial Data Accuracy* (NSSDA), published by the Federal Geographic Data Committee (FGDC) in 1998, was developed to report accuracy of digital geospatial data at the 95% confidence level as a function of RMSE values in X, Y, and Z at ground scale, unconstrained by map scale or contour interval. The NSSDA states,

  > "The reporting standard in the horizontal component is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95% of the time. The reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95% of the time. The reporting accuracy standard should be defined in metric (International System of Units, SI) units. However, accuracy will be reported in English units (inches and feet) where point coordinates or elevations are reported in English units. The NSSDA uses root-mean-square error (RMSE) to estimate positional accuracy. Accuracy reported at the 95% confidence level means that 95% of

the positions in the data set will have an error with respect to true ground position that is equal to or smaller than the reported accuracy value."

The NSSDA does not define threshold accuracy values, stating, "Agencies are encouraged to establish thresholds for their product specifications and applications and for contracting purposes." Equations for converting RMSE values in X, Y, and Z into horizontal and vertical accuracies at the 95% confidence levels are provided in Appendix 3-A of the NSSDA. The NSSDA assumes normal error distributions, with systematic errors eliminated as well as possible.

- The National Digital Elevation Program (NDEP) published the *NDEP Guidelines for Digital Elevation Data* in 2004, recognizing that lidar errors of Digital Terrain Models (DTMs) do not necessarily follow a normal distribution in vegetated terrain. The NDEP developed Fundamental Vertical Accuracy (FVA), Supplemental Vertical Accuracy (SVA) and Consolidated Vertical Accuracy (CVA). The FVA is computed in non-vegetated, open terrain only, and is based on the NSSDA's $RMSE_V$ * 1.9600 because elevation errors in open terrain do tend to follow a normal distribution, especially with a large number of checkpoints. SVA is computed in individual land cover categories, and CVA is computed in all land cover categories combined. Both SVA and CVA are based on 95th percentile errors (instead of RMSE multipliers) because errors in DTMs in other land cover categories—especially vegetated/forested areas—do not necessarily follow a normal distribution. While the NDEP Guidelines do establish alternative procedures for testing and reporting the vertical accuracy of elevation data sets when errors are not normally distributed, they do not provide accuracy thresholds or quality levels.
- The *ASPRS Guidelines: Vertical Accuracy Reporting for Lidar Data*, published in 2004, essentially endorsed the NDEP Guidelines, including the NDEP Guidelines' FVA, SVA and CVA reporting models and its standards for handling elevation errors when the errors are not normally distributed. Similarly to the NDEP Guidelines, the ASPRS 2004 Guidelines do not provide accuracy thresholds or quality levels.
- Between 1998 and 2010, the Federal Emergency Management Agency (FEMA) published *Guidelines and Specifications for Flood Hazard Mapping Partners* that included $RMSE_V$ thresholds, as well as requirements for testing and reporting the vertical accuracy separately for all major land cover categories within floodplains being mapped for the National Flood Insurance Program (NFIP). In its *Procedure Memorandum No. 61 – Standards for Lidar and Other High Quality Digital Topography*, dated 27 September 2010, FEMA endorsed the *USGS Draft Lidar Base Specifications V13*, relevant to floodplain mapping in areas of highest flood risk only, with poorer accuracy and point density in areas of lesser flood risks. USGS's draft V13 specification subsequently became the *USGS Lidar Base Specification V1.0* specification, summarized below. FEMA's Guidelines and Procedures only address requirements for flood risk mapping, and do not represent universal practices for accuracy standards.
- In 2012, USGS published its *Lidar Base Specification, Version 1.0*, which is based on an $RMSE_V$ of 12.5 cm in open terrain and elevation post spacing no greater than 1 to 2 meters. FVA, SVA, and CVA values are also specified. This document is not a standard, but a specification for lidar data

used to populate the National Elevation Data set (NED) at 1/9th arc-second post spacing (~3 meters) for gridded Digital Elevation Models (DEMs).

- In 2012, USGS also published the final report of the *National Enhanced Elevation Assessment* (NEEA), which considered five Quality Levels of enhanced elevation data to satisfy nationwide requirements, with each Quality Level having different $RMSE_V$ and point density thresholds. With support from the National Geospatial Advisory Committee (NGAC), USGS subsequently developed its new 3D Elevation Program (3DEP) based on lidar Quality Level 2 data with 1' equivalent contour accuracy ($RMSE_Z < 10$ cm) and point density of 2 points per square meter for all states except Alaska—for Alaska, IFSAR Quality Level 5 data is specified, meaning the $RMSE_V$ must be between 1 and 2 meters, and must have 5 meter post spacing. The 3DEP lidar data is expected to be high resolution and capable of supporting DEMs at 1 meter resolution. The 3DEP Quality Level 2 and Quality Level 5 products are expected to become industry standards for digital elevation data, effectively replacing the older elevation data from the USGS's National Elevation Data set.
- The latest *USGS Lidar Base Specification, Version 1.2* was published in 2014 to accommodate Lidar Quality Levels 0, 1, 2 and 3.
- In this version of the Standards, the accuracy measure of 95% confidence level is removed in favor of only reporting the RMSE values, due to the confusion it creates for both data producers and users of the Standards. However, when 95% confidence interval reporting is required, readers should refer to Section B.7.

A.2 A New Standard for a New Era

The current Standards were developed in response to the pressing need within the GIS and mapping community for new Standards that embrace the digital nature of current geospatial technologies. The following are some of the justifications for the development of the new Standards:

- Legacy map accuracy Standards, such as the ASPRS 1990 Standards and the NMAS of 1947, are outdated. Many of the data acquisition and mapping technologies that these Standards were based on are no longer used. More recent advances in mapping technologies can now produce better quality and higher accuracy geospatial products and maps. New Standards are needed to reflect these advances.
- Legacy map accuracy Standards were designed to deal with plotted or drawn maps as the only mediums with which to represent geospatial data. The concept of hardcopy map scale dominated the mapping industry for decades. Digital mapping products need different measures (besides scale) that are suitable for the digital medium that users now utilize.
- Within the past two decades (during the transition period between the hardcopy and softcopy mapping environments), most standard measures for relating GSD and map scale to the final mapping accuracy were inherited from photogrammetric practices using scanned film. With advances in technology and in our knowledge of mapping processes and mathematical modeling, new mapping processes and methodologies have become much more sophisticated. Mapping accuracy can no longer be associated with the camera geometry and flying altitude

alone; many other factors now influence the accuracy of geospatial mapping products. Such factors include: the quality of camera calibration parameters, the quality and size of the Charged Coupled Device (CCD) used in the digital camera CCD array, the amount of imagery overlap, the quality of parallax determination or photo measurements, the quality of the GPS signal, the quality and density of ground control, the quality of the aerial triangulation solution, the capability of the processing software to handle GPS drift and shift and camera self-calibration, and the digital terrain model used for the production of orthoimagery. These factors can vary widely from project to project, depending on the sensor used and specific methodology. For these reasons, existing accuracy measures based on map scale, film scale, GSD, c-factor, and scanning resolution no longer apply to the vast majority of current geospatial mapping practices.

- Elevation products from the new technologies and active sensors such as lidar and IFSAR are not considered in legacy mapping standards. New accuracy standards are needed to address elevation products derived from these technologies.

A.2.1 Mapping Practices During the Film-based Era

In the early history of photogrammetric mapping, film was the only medium capable of recording an aerial photographic session. During that period, film scale, film-to-map enlargement ratio, and c-factor were used to define final map scale and map accuracy, and a film-to-map enlargement ratio value of 6 and a c-factor value of 1800 to 2000 were widely accepted and used. C-factor was used to determine the flying height based on the desired contour interval via the following formula:

$$c\text{-}factor = \frac{flying\ height}{contour\ interval}$$

Values in Table A.1 were historically utilized by the mapping community for photogrammetric mapping from film:

Table A.1 Common Photography Scales using Camera with 9” Film Format and 6” Lens

Film Scale	1” = 300’	1” = 600’	1” = 1200’	1” = 2400’	1” = 3333’
	1:3,600	1:7,200	1:14,400	1:28,800	1:40,000
Flying Height	1,800’ / 550 m	3,600’ / 1,100 m	7,200’ / 2,200 m	14,400’ / 4,400 m	20,000’ / 6,100 m
Map Scale	1” = 50’	1” = 100’	1” = 200’	1” = 400’	1” = 1000’
	1:600	1:1,200	1:2,400	1:4,800	1:12,000

A.2.2 Mapping Practices During the Softcopy Photogrammetry Era

When the softcopy photogrammetric mapping approach was first introduced to the mapping industry in the early 1990s, large format film scanners were used to convert aerial film to digital imagery. The mapping community needed guidelines for relating the scanning resolution of the film to the supported map scale and contour interval used by legacy standards to specify map accuracies. Table A.2 relates the resulting GSD of the scanned film and the supported map scale and contour interval derived from film-based cameras at different flying altitudes. Table A.2 assumes a scan resolution of 21 microns, as that was in common use for many years. The values in Table A.2 are derived based on the commonly used film-to-map enlargement ratio of 6 and a c-factor of 1800. Such values were endorsed and widely used by both map users and data producers during and after the transition period from film to the softcopy environment.

Table A.2 Relationship Between Film Scale and Derived Map Scale

	Common Photography Scales (with 9" film format camera and 6" lens)			
Photo Scale	1" = 300'	1" = 600'	1" = 1200'	1" = 2400'
	1:3,600	1:7,200	1:14,400	1:28,800
Flying Height	1,800' / 550 m	3,600' / 1,100 m	7,200' / 2,200 m	14,400' / 4,400 m
Approximate Ground Sampling Distance (GSD) of Scan	0.25' / 7.5 cm	0.50' / 0.15 m	1.0' / 0.3 m	2.0' / 0.6 m
	Supported Map/Orthoimagery Scales and Contour Intervals			
GSD	3" / 7.5 cm	6" / 15 cm	1.0' / 30 cm	2.0' / 60 cm
C.I.	1.0' / 30 cm	2.0' / 60 cm	4' / 1.2 m	8' / 2.4 m
Map Scale	1" = 50'	1" = 100'	1" = 200'	1" = 400'
	1:600	1:1,200	1:2,400	1:4,800

A.2.3 Mapping Practices During the Digital Sensors Photogrammetry Era

Since they were first introduced to the mapping community in 2000, digital large format metric mapping cameras have become the main aerial imagery acquisition system utilized for geospatial mapping. The latest generation of digital metric mapping cameras have enhanced optics quality, extended radiometric resolution through a higher dynamic range, finer CCD resolution, more durable body construction, and more precise electronics. These new camera technologies, coupled with advances in the airborne GPS and mathematical modeling performed by modern photogrammetric processing software, make it possible to extend the limits on the flying altitude and still achieve high quality mapping products of equal or greater accuracy than what could be achieved with older technologies.

Many of the rules that have influenced photogrammetric practices for the last six or seven decades (such as those outlined in Sections A.2.1 and A.2.2 above) are based on the capabilities of outdated technologies and techniques. For instance, standard legacy guidelines, like the film-to-map enlargement ratio value of 6 and c-factors between 1800 to 2000, are based on the limitations of optical-mechanical photogrammetric plotters and aerial film resolution. These legacy rules no longer apply to mapping processes utilizing digital mapping cameras and current technologies.

Unfortunately, in the absence of clear, updated guidelines, outdated practices and guidelines intended for older technologies with very different limitations are commonly misapplied to newer technologies. Most users and data producers still utilize the figures given in Table A.2 for associating the imagery GSD to a supported map scale and associated accuracy, even though these associations are based on scanned film and do not apply to current digital sensors. New relationships between imagery GSD and product accuracy are needed to account for the full range of factors that influence the accuracy of mapping products derived from digital sensors.

APPENDIX B — DATA ACCURACY AND QUALITY EXAMPLES (NORMATIVE)

B.1 Aerial Triangulation and Ground Control Accuracy Examples

Sections 7.7 and 7.8 describe the accuracy requirements for aerial triangulation, IMU, and ground control points relative to product accuracies. These requirements differ depending on whether the products include elevation data. Tables B.1 and B.2 provide an example of how these requirements can be applied to a typical product with a horizontal accuracy of $RMSE_H$ equal to 50 cm.

Table B.1 Aerial Triangulation and Ground Control Accuracy Requirements- For Orthoimagery and/or Planimetric Data Only

Product Accuracy ($RMSE_H$) (cm)	A/T Accuracy		Ground Control Accuracy	
	$RMSE_H$ (cm)	$RMSE_V$ (cm)	$RMSE_H$ (cm)	$RMSE_V$ (cm)
50	*25*	*50*	*25*	*50*

Table B.2 Aerial Triangulation and Ground Control Accuracy Requirements- For Orthoimagery and/or Planimetric Data and Elevation Data

Product Accuracy ($RMSE_H$) (cm)	A/T Accuracy		Ground Control Accuracy	
	$RMSE_H$ (cm)	$RMSE_V$ (cm)	$RMSE_H$ (cm)	$RMSE_V$ (cm)
50	*25*	*25*	*25*	*25*

B.2 Digital Orthoimagery Horizontal Accuracy Classes

This Standard does not associate product accuracy with the GSD of the source imagery, pixel size of the orthoimagery, or map scale for scaled maps.

The relationship between the recommended $RMSE_H$ accuracy class and the orthoimagery pixel size varies depending on the imaging sensor characteristics and the specific mapping processes used. The appropriate horizontal accuracy class must be negotiated and agreed upon between the end user and the data producer, based on specific project needs and design criteria. This section provides some general guidance to assist in making these decisions.

Table B.3 presents examples of 24 horizontal accuracy classes and their associated orthoimagery quality criteria according to the requirements outlined in Section 7.3.

Table B.3 Common Horizontal Accuracy Classes According to the New Standard[3]

Horizontal Accuracy Class	$RMSE_H$ (cm)	Orthoimage Mosaic Seamline Maximum Mismatch (cm)
0.6	*0.6*	*1.3*
1.3	*1.3*	*2.5*
2.5	*2.5*	*5.0*
5.0	*5.0*	*10.0*
7.5	*7.5*	*15.0*
10.0	*10.0*	*20.0*
12.5	*12.5*	*25.0*
15.0	*15.0*	*30.0*
17.5	*17.5*	*35.0*
20.0	*20.0*	*40.0*
22.5	*22.5*	*45.0*
25.0	*25.0*	*50.0*
27.5	*27.5*	*55.0*
30.0	*30.0*	*60.0*
45.0	*45.0*	*90.0*
60.0	*60.0*	*120.0*
75.0	*75.0*	*150.0*
100.0	*100.0*	*200.0*
150.0	*150.0*	*300.0*
200.0	*200.0*	*400.0*
250.0	*250.0*	*500.0*
300.0	*300.0*	*600.0*
500.0	*500.0*	*1000.0*
1000.0	*1000.0*	*2000.0*

Achieving the highest level of accuracy requires specialized considerations according to sensor type, ground control density, ground control accuracies, and overall project design. In many cases, these considerations may result in unrealistic or unreasonable costs. As such, the highest achievable accuracies may not be appropriate for all projects. Many geospatial mapping projects require high-resolution and high-quality imagery, but do not require the highest level of positional accuracy. This is particularly true for map updating or similar projects where the intent is to upgrade the image resolution, but still leverage existing elevation model data and ground control data that may have been originally developed according to a lower accuracy standard.

[3] For Tables B.3 through B.8, values were rounded to the nearest mm after full calculations were performed with all decimal places.

B.3 Digital Planimetric Data Horizontal Accuracy Classes

Table B.4 presents 24 common horizontal accuracy classes for digital planimetric data, approximate GSD of source imagery for high-accuracy planimetric data, and equivalent map scales per legacy NMAS and ASPRS 1990 Accuracy Standards. In Table B.4, the values for the approximate GSD of source imagery only apply to imagery derived from common large- and medium-format metric cameras. The range of the approximate GSD of source imagery is only provided as a general recommendation, based on the current state of sensor technologies and mapping practices, and it should not be used to reference product accuracy. Different ranges may be considered in the future depending on technological advances and mapping practices.

Table B.4 Horizontal Accuracy/Quality Examples for High Accuracy Digital Planimetric Data

ASPRS Edition 2 (2023)			Equivalent to Map Scale in		Equivalent to Map Scale in NMAS
Horizontal Accuracy Class	$RMSE_H$ (cm)	Approximate GSD of Source Imagery (cm)	ASPRS 1990 Class 1	ASPRS 1990 Class 2	
0.63	*0.63*	*0.31 to 0.63*	*1:25*	*1:12.5*	*1:16*
1.25	*1.25*	*0.63 to 1.25*	*1:50*	*1:25*	*1:32*
2.5	*2.5*	*1.25 to 2.5*	*1:100*	*1:50*	*1:63*
5.0	*5.0*	*2.5 to 5.0*	*1:200*	*1:100*	*1:127*
7.5	*7.5*	*3.8 to 7.5*	*1:300*	*1:150*	*1:190*
10.0	*10.0*	*5.0 to 10.0*	*1:400*	*1:200*	*1:253*
12.5	*12.5*	*6.3 to12.5*	*1:500*	*1:250*	*1:317*
15.0	*15.0*	*7.5 to 15.0*	*1:600*	*1:300*	*1:380*
17.5	*17.5*	*8.8 to 17.5*	*1:700*	*1:350*	*1:444*
20.0	*20.0*	*10.0 to 20.0*	*1:800*	*1:400*	*1:507*
22.5	*22.5*	*11.3 to 22.5*	*1:900*	*1:450*	*1:570*
25.0	*25.0*	*12.5 to 25.0*	*1:1000*	*1:500*	*1:634*
27.5	*27.5*	*13.8 to 27.5*	*1:1100*	*1:550*	*1:697*
30.0	*30.0*	*15.0 to 30.0*	*1:1200*	*1:600*	*1:760*
45.0	*45.0*	*22.5 to 45.0*	*1:1800*	*1:900*	*1:1141*
60.0	*60.0*	*30.0 to 60.0*	*1:2400*	*1:1200*	*1:1521*
75.0	*75.0*	*37.5 to 75.0*	*1:3000*	*1:1500*	*1:1901*
100.0	*100.0*	*50.0 to 100.0*	*1:4000*	*1:2000*	*1:2535*
150.0	*150.0*	*75.0 to 150.0*	*1:6000*	*1:3000*	*1:3802*
200.0	*200.0*	*100.0 to 200.0*	*1:8000*	*1:4000*	*1:5069*
250.0	*250.0*	*125.0 to 250.0*	*1:10000*	*1:5000*	*1:6337*
300.0	*300.0*	*150.0 to 300.0*	*1:12000*	*1:6000*	*1:7604*
500.0	*500.0*	*250.0 to 500.0*	*1:20000*	*1:10000*	*1:21122*
1000.0	*1000.0*	*500.0 to 1000.0*	*1:40000*	*1:20000*	*1:42244*

B.4 Digital Elevation Data Vertical Accuracy Classes

Table B.5 provides vertical accuracy examples and other quality criteria for ten common vertical accuracy classes. Table B.6 compares the ten vertical accuracy classes with contour intervals from legacy ASPRS 1990 and NMAS 1947 Standards. Table B.7 provides ten vertical accuracy classes with the recommended lidar point density suitable for each of them.

Table B.5 Vertical Accuracy/Quality Examples for Digital Elevation Data

Vertical Accuracy Class	Absolute Accuracy		Data Internal Precision (where applicable)		
	NVA $RMSE_V$ (cm)	VVA $RMSE_V$ (cm)	Within-Swath Smooth Surface Precision Max Diff (cm)	Swath-to-Swath Non-Vegetated RMS_{DZ} (cm)	Swath-to-Swath Non-Vegetated Max Diff (cm)
1-cm	*≤ 1.0*	*As found*	*≤ 0.6*	*≤ 0.8*	*≤ 1.6*
2.5-cm	*≤ 2.5*	*As found*	*≤ 1.5*	*≤ 2.0*	*≤ 4.0*
5-cm	*≤ 5.0*	*As found*	*≤ 3.0*	*≤ 4.0*	*≤ 8.0*
10-cm	*≤ 10.0*	*As found*	*≤ 6.0*	*≤ 8.0*	*≤ 16.0*
15-cm	*≤ 15.0*	*As found*	*≤ 9.0*	*≤ 12.0*	*≤ 24.0*
20-cm	*≤ 20.0*	*As found*	*≤ 12.0*	*≤ 16.0*	*≤ 32.0*
33.3-cm	*≤ 33.3*	*As found*	*≤ 20.0*	*≤ 26.7*	*≤ 53.3*
66.7-cm	*≤ 66.7*	*As found*	*≤ 40.0*	*≤ 53.3*	*≤ 106.7*
100-cm	*≤ 100.0*	*As found*	*≤ 60.0*	*≤ 80.0*	*≤ 160.0*
333.3-cm	*≤ 333.3*	*As found*	*≤ 200.0*	*≤ 266.7*	*≤ 533.3*

Table B.6 Vertical Accuracy of the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 Compared to Legacy Standards

Vertical Accuracy Class	NVA $RMSE_V$ (cm)	Equivalent Class 1 Contour Interval per ASPRS 1990 (cm)	Equivalent Class 2 Contour Interval per ASPRS 1990 (cm)	Equivalent Contour Interval per NMAS (cm)
1-cm	*1.0*	*3.0*	*1.5*	*3.29*
2.5-cm	*2.5*	*7.5*	*3.8*	*8.22*
5-cm	*5.0*	*15.0*	*7.5*	*16.45*
10-cm	*10.0*	*30.0*	*15.0*	*32.90*
15-cm	*15.0*	*45.0*	*22.5*	*49.35*
20-cm	*20.0*	*60.0*	*30.0*	*65.80*
33.3-cm	*33.3*	*99.9*	*50.0*	*109.55*
66.7-cm	*66.7*	*200.1*	*100.1*	*219.43*
100-cm	*100.0*	*300.0*	*150.0*	*328.98*
333.3-cm	*333.3*	*999.9*	*500.0*	*1096.49*

Table B.7 Examples of Vertical Accuracy and Recommended Lidar Point Density for Digital Elevation Data according to the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023

Vertical Accuracy Class	*NVA $RMSE_V$ (cm)*	*Recommended Minimum NPD[4] (pls/m^2)*	*Recommended Maximum NPS[5] (m)*
1-cm	*1.0*	*≥ 20*	*≤ 0.22*
2.5-cm	*2.5*	*16*	*0.25*
5-cm	*5.0*	*8*	*0.35*
10-cm	*10.0*	*2*	*0.71*
15-cm	*15.0*	*1*	*1.0*
20-cm	*20.0*	*0.5*	*1.4*
33.3-cm	*33.3*	*0.25*	*2.0*
66.7-cm	*66.7*	*0.1*	*3.2*
100-cm	*100.0*	*0.05*	*4.5*
333.3-cm	*333.3*	*0.01*	*10.0*

B.5 Relating ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 Values to Legacy ASPRS 1990 Accuracy Values

In this section, examples are provided for users who wish to compare these Standards to the legacy ASPRS 1990 Accuracy Standards for Large-Scale Maps. A major advantage of these Standards is that accuracy statements are based on RMSE at ground scale. The legacy Standards refer to RMSE, but define Class 1 as higher accuracy and Classes 2 and 3 as lower accuracy, while these Standards refer to the map accuracy by the value of RMSE without defining discrete numbered classes. The following examples illustrate the procedures users can follow to relate horizontal and vertical accuracy values between these Standards and the legacy ASPRS 1990 Accuracy Standards for Large-Scale Maps.

Example 1: Relating the Horizontal Accuracy of a Map or Orthorectified Image calculated with the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the Legacy ASPRS Map Standards of 1990

Given a map or orthoimagery with an accuracy of $RMSE_H$ = 15 cm according to the 2023 Standards, compute the equivalent accuracy and map scale according to the legacy 1990 Standards.

Solution:

1. According to the legacy 1990 Standards, horizontal accuracy is represented by $RMSE_X$ or $RMSE_Y$. If we assume that $RMSE_X = RMSE_Y$, then:

$$RMSE_H = \sqrt{RMSE_X{}^2 + RMSE_Y{}^2}, \text{ or}$$

[4] Nominal Pulse Density (NPD) and Nominal Pulse Spacing (NPS) are geometrically inverse methods to measure the pulse density or spacing of a lidar collection. NPD is a ratio of the number of points to the area in which they are contained, and is typically expressed as pulses per square meter (ppsm or pts/m2). NPS is a linear measure of the typical distance between points, and is most often expressed in meters. Although either expression can be used for any data set, NPD is usually used for lidar collections with NPS < 1, and NPS is used for those with NPS ≥ 1. Both measures are based on all first- or last-return lidar point data, as these return types each reflect the number of pulses. Conversion between NPD and NPS is accomplished using the equation $NPS = 1/\sqrt{NPD}$ or $NPD = 1/NPS^2$. Although typical point densities are listed for specified vertical accuracies, users may select higher or lower point densities according to project requirements and complexity of surfaces to be modeled.

$$RMSE_X \text{ or } RMSE_Y = RMSE_H /1.414 = 10.61 \text{ cm}$$

2. To find the equivalent map scale according to the legacy 1990 Standards, follow the following steps:

   a. Multiply the $RMSE_X$ or $RMSE_Y$ value in centimeters by 40 to compute the map scale factor (MSF) for a Class 1 map:

      MSF = 10.61 (cm) x 40 = 424

   b. The map scale according to the legacy 1990 Standards are:

      Map Scale = 1:MSF or 1:424 Class 1;

   The accuracy value of $RMSE_H$ = 15 cm is also equivalent to Class 2 accuracy for a map with a scale of 1:212.

Example 2: Relating the Vertical Accuracy of an Elevation Data Set calculated with the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the Legacy ASPRS Map Standards of 1990

Given an elevation data set with a vertical accuracy of $RMSE_V$ = 10-cm according to Edition 2 of the Standards, compute the equivalent contour interval according to the legacy 1990 Standards.

Solution:

The legacy ASPRS map Standards of 1990 state:

> *"The limiting rms error in elevation is set by the Standard at one-third the indicated contour interval for well-defined points only. Spot heights shall be shown on the map within a limiting rms error of one-sixth of the contour interval."*

Because both Standards utilize the same RMSE measure to express vertical accuracy, then the accuracy of the elevation data set according to the legacy 1990 Standards are:

$RMSE_V$ = 10 cm

Using the legacy 1990 Standards' accuracy measure of $RMSE_V$ = 1/3 * contour interval (CI):

CI = 3 * $RMSE_V$ = 3 * 10 cm = 30-cm for Class 1, or

CI = 15-cm for Class 2

If the user is interested in evaluating the spot height requirement according to the legacy 1990 Standards, the accuracy for spot heights is required to be twice the accuracy of the contours (one-sixth versus one-third for the contours) or:

For 30 cm CI, the required spot height accuracy, $RMSE_V$ = 1/6 * 30-cm = 5 cm

Data with $RMSE_V$ = 10-cm would support Class 2 accuracy for spot elevations at this contour interval.

B.6 Relating ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 Values to Legacy NMAS 1947 Accuracy Values

In this section, examples are provided for users who wish to relate these Standards to the legacy National Map Accuracy Standards (NMAS) of 1947.

The legacy 1947 Standards use two accuracy criteria based on map scale: "1/30 inch for map scales larger than 1:20,000" and "1/50 inch for maps with a scale of 1:20,000 or smaller." Here horizontal accuracy refers to the Circular Map Accuracy Standard (CMAS) or Circular Error at the 90% Confidence Level (CE90).

Regarding vertical accuracy, the legacy 1947 Standards state:

> *"Vertical Accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval."*

Here vertical accuracy refers to the Vertical Map Accuracy Standard (VMAS) or Linear Error at the 90% Confidence Level (LE90).

The following examples illustrate the procedures users can follow to relate horizontal and vertical accuracy values between ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 and the legacy 1947 Standards.

Example 3: Relating the Horizontal Accuracy of a Map or Orthorectified Image calculated with the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the Legacy National Map Accuracy Standards of 1947

Given a map or orthoimagery with an accuracy of $RMSE_X$ = $RMSE_Y$ = 15-cm according to the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023, compute the equivalent accuracy and map scale according to the legacy 1947 Standards.

Solution:

$RMSE_H$ = 15-cm is representative of data sets typically used to create large-scale maps, so for this example, we will apply the criterion for scales larger than 1:20000.

Use the factor "1/30 inch":

$$CMAS\ (CE90) = 2.1460 * RMSE_H$$

$$CE90 = 2.1460 * 15\ cm = 32.19\ cm$$

Convert CE90 to feet:

$$32.19\ cm = 1.0561\ ft$$

Use the NMAS accuracy relation of CE90 = 1/30" on the map to compute the map scale:

CE90 = 1/30 * ground distance covered by an inch of the map, or

ground distance covered by an inch of the map = CE90 * 30

ground distance covered by an inch of the map = 1.0561 ft x 30 = 31.683 ft

The equivalent map scale according to NMAS is 1” = 31.68’, or 1:380

Example 4: Relating the Vertical Accuracy of an Elevation Data Set calculated with the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the Legacy National Map Accuracy Standards of 1947

Given an elevation data set with a vertical accuracy of $RMSE_V$ = 10-cm according to the 2023 Standards, compute the equivalent contour interval according to the legacy 1947 Standards.

Solution:

As mentioned earlier, the legacy 1947 Standards state that:

> *“Vertical Accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval.”*

Compute error at 90% confidence using $RMSE_V$:

$$VMAS\ (LE90) = 1.6449 * RMSE_V = 1.6449 * 10\ cm = 16.449\ cm$$

Compute the contour interval (CI) using the following criteria set by the NMAS:

$$VMAS\ (LE90) = \tfrac{1}{2}\ CI, \text{ or}$$

$$CI = 2 * LE90 = 2 * 16.449\ cm = 32.9\ cm$$

B.7 Relating ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 Values to the FGDC National Standard for Spatial Data Accuracy (NSSDA)

In this section, examples are provided for users who wish to relate these Standards to the FGDC National Standard for Spatial Data Accuracy (NSSDA).

Example 5: Relating the Horizontal Accuracy of a Map or Orthorectified Image calculated with ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the FGDC National Standard for Spatial Data Accuracy (NSSDA)

Given a map or orthoimagery with an accuracy of $RMSE_H$ = 15-cm according to the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023, compute the equivalent accuracy and map scale according to the FGDC National Standard for Spatial Data Accuracy (NSSDA).

Solution:

According to NSSDA, the horizontal positional accuracy is estimated at 95% confidence level using the following formula:

$$Accuracy_{H95\%} = 1.7308 * RMSE_H = 1.7308 * 15\ cm = 25.96\ cm$$

Example 6: Relating the Vertical Accuracy of an Elevation Data Set calculated with the ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 2, 2023 to the FGDC National Standard for Spatial Data Accuracy (NSSDA)

Given an elevation data set with a vertical accuracy of $RMSE_V$ = 10-cm according to the 2023 Standards, compute the vertical accuracy according to the FGDC National Standard for Spatial Data Accuracy (NSSDA).

Solution:

According to NSSDA, the vertical accuracy of an elevation data set is estimated at 95% confidence level using the following formula:

$$Accuracy_{V95\%} = 1.96 * RMSE_V$$

$$Accuracy_{V95\%} = 1.96 * 10\text{ cm} = 19.60\text{ cm}$$

B.8 Estimating Horizontal Accuracy of Lidar Data

As described in Section 7.6, the horizontal error component of lidar is largely a function of GNSS positional error, IMU angular error, and flying height. These are not the only contributing factors to horizontal error, but, taken together, they can provide a rough estimate of the total horizontal error, which can be helpful when planning data acquisition where horizontal accuracy is a concern.

If the radial horizontal positional error of the GNSS is assumed to be equal to 0.10 m (based on 0.07 m in either X or Y), and the IMU error is assumed to be 10.0 arc-seconds (0.0027 degrees) for the roll and pitch and 15.0 arc-seconds (0.00417 degree) for the heading, Table B.8 can be used to predict the horizontal accuracy of the lidar point ($RMSE_H$) captured within a 40-degree field of view at different flying heights above mean terrain (FH).

Table B.8 Estimated Horizontal Error ($RMSE_H$) as a Function of GNSS Error, IMU Error, and Flying Height

Flying Height (m)	GNSS Error (cm)	IMU Roll/Pitch Error (arc-sec)	IMU Heading Error (arc-sec)	$RMSE_H$ (cm)
500	*10*	*10*	*15*	*10.7*
1,000	*10*	*10*	*15*	*12.9*
1,500	*10*	*10*	*15*	*15.8*
2,000	*10*	*10*	*15*	*19.2*
2,500	*10*	*10*	*15*	*22.8*
3,000	*10*	*10*	*15*	*26.5*
3,500	*10*	*10*	*15*	*30.4*
4,000	*10*	*10*	*15*	*34.3*
4,500	*10*	*10*	*15*	*38.2*
5,000	*10*	*10*	*15*	*42.0*

Each lidar system has its own specifications for GNSS and IMU error; therefore, the values in Table B.8 should be modified according to the equation in section 7.5.

B.9 Elevation Data Accuracy vs. Elevation Data Quality

In aerial photography and photogrammetry, the horizontal and vertical accuracy of individual points are largely dependent on the scale and resolution (GSD) of the source imagery. Larger-scale imagery flown at a lower altitude produces smaller GSD and higher measurement accuracy. Users have, quite naturally, come to equate higher-resolution imagery (smaller GSD) with higher accuracy and higher quality.

In airborne topographic lidar, this is not entirely the case. For many typical lidar collections, the maximum accuracy attainable is limited by the combined error budget for all components of the lidar system, including laser ranging error, GNSS positional error, IMU angular error, and encoder error. Increasing the resolution of the data by increasing point density does not change the system error. Beyond the lidar system, the data must also be properly controlled, calibrated, boresighted, and processed. Errors introduced during any of these steps will affect the accuracy of the data, regardless of the point density. That said, high density lidar data is usually of higher *quality* than low density data, and the increased quality can manifest as *apparently* higher accuracy.

To accurately represent a complex terrain surface, higher point density is required to capture surface details and linear features, such as curbs and micro drainage features. In vegetated areas, where many lidar pulses are fully reflected before reaching the ground, a higher density data set tends to be more accurate because more points will penetrate through. More ground points will result in more accurate interpolation between points and, thus, improved surface definition. The need for dense ground points is greatest in variable or complex surfaces, such as mountainous terrain, where generalized interpolation between points would not accurately model all changes in the surface.

However, while the use of denser data for complex surface representation improves the accuracy of the derived surface at locations between the lidar measurements, it does not necessarily make the individual lidar measurements any more accurate. For more details on the topic, consult Addendum I of these Standards.

Increased density may not significantly improve the accuracy of the terrain model in flat, open terrain where interpolation between points may still adequately represent the ground surface. However, higher density data may still improve the quality of the data by adding additional detail to the final surface model, improving detection of edges for breaklines, and increasing the confidence of the relative accuracy in swath overlap areas by reducing interpolation within the data set. High density data collection will also produce higher resolution lidar intensity images, which is always useful when using intensity data to aid in interpretation, edge detection, and feature extraction.

APPENDIX C — ACCURACY TESTING AND REPORTING GUIDELINES (NORMATIVE)

C.1 Checkpoint Requirements

Checkpoints used to assess product accuracy should be derived from an independent set of points that was not already used in processing or calibrating the product under evaluation. Checkpoints should have higher accuracy than the product being evaluated; they can be either field surveyed or derived from another product of higher accuracy.

The total number of points and their spatial distribution are both important in accuracy assessment. Legacy standards and guidelines typically specified a minimum number of checkpoints, and, in some cases, the type of land cover where they were to be acquired, but they did not define or characterize the spatial distribution of the points. A quantitative methodology for characterization and specification of the spatial distribution of checkpoints which accounts for land cover type and project shape does not currently exist. ASPRS encourages research into this topic for future revisions of these Standards. In the interim, this Appendix provides general recommendations and guidelines for quantity and placement of checkpoints for accuracy assessment.

C.2 Accuracy of Checkpoints

According to these Standards, checkpoints should be at least twice the accuracy of the final product specification. Checkpoints of suspect quality should not be used for product accuracy assessment. Individual checkpoints showing errors larger than 3 * $\mathrm{RMSE}_{\mathrm{H}_1}$ or $\mathrm{RMSE}_{\mathrm{V}_1}$ should be investigated. Addendum V of these Standards should be consulted when surveying checkpoints.

C.3 Number of Checkpoints

Table C.1 lists ASPRS recommendations for the number of checkpoints to be used for the horizontal accuracy testing of digital orthoimagery and planimetric data sets, and for the vertical accuracy of elevation data. For vertical accuracy testing, users of the Standards should follow these recommendations:

Testing Non-Vegetated Vertical Accuracy (NVA): The number of checkpoints should be based on Table C.1.

Testing Vegetated Vertical Accuracy (VVA): If the project requires the VVA to be tested, a minimum of thirty (30) VVA checkpoints—regardless of the project area—shall be collected proportionally across the primary vegetated land cover categories found throughout the project area of interest. Typical vegetated land cover categories include weeds and crops, brush lands, and fully-forested land. The data user and data producer may agree to collect a larger number of checkpoints. To avoid situations where the errors in checkpoints in vegetated terrain may not follow a random distribution, no combined statistical terms, such as RMSE_v, should be used in evaluating the results of the test. In other words, only individual elevation differences (i.e. errors) for each checkpoint shall be used in the evaluation.

The project area should be divided based on land cover into non-vegetated and vegetated areas. Then, the appropriate number of checkpoints should be acquired for each to test the horizontal accuracy of the digital orthophotos and planimetric data and the vertical accuracy of the elevation data. For the non-vegetated areas, appropriate checkpoint quantity should be extracted from table C.1. For each vegetated area, an additional 30 checkpoints should be acquired to evaluate vertical accuracy of elevation data.

For projects where the 30-checkpoint minimum is not feasible (e.g., the project is testing too small of an area, or is working under budget constraints), an accuracy verification using a smaller number of checkpoints should be reported according to the statements provided in section 7.15 of these Standards.

Table C.1 Recommended Number of Checkpoints for Horizontal Accuracy and NVA Testing Based on Project Area

Project Area (Square Kilometers)	*Total Number of Checkpoints for NVA*
≤1000[5]	*30*
1001-2000	*40*
2001-3000	*50*
3001-4000	*60*
4001-5000	*70*
5001-6000	*80*
6001-7000	*90*
7001-8000	*100*
8001-9000	*110*
9001-10000	*120*
>10000	*120*

The recommended number and distribution of NVA and VVA checkpoints may vary depending on the importance of different land cover categories and client requirements. The number of checkpoints put forward in Table C.1 are only recommendations based on best practices. Data producers and data users may agree to alter such requirements based on expected accuracy, project area and scope, terrain difficulties, area accessibility, and budget.

C.4 Distribution of Vertical Checkpoints Across Land Cover Types

The recommended number of checkpoints should be distributed evenly around the vegetated and non-vegetated areas of the project. There may be exceptions depending on the nature of the terrain and land cover; however, efforts should be made to assure that the best possible checkpoint distribution is achieved.

ASPRS recognizes that some project areas are primarily non-vegetated, while other areas are primarily vegetated. For these reasons, the distribution of checkpoints can vary based on the general proportion of vegetated to non-vegetated areas in the project area. Checkpoints should generally be distributed proportionally among the various vegetated land cover types in the project. In areas where difficult terrain and transportation limitations may render some land cover types inaccessible, the desired spatial distribution of checkpoints across land cover types may not be possible. In these situations, data

[5] For very small projects where the use of 30 checkpoints is not feasible, report the accuracy as suggested in section 7.15.

producers should consult with their clients and use their best professional judgment in selecting checkpoint locations.

The recommendations in sections C.1 through C.3 intentionally offer a fair amount of discretion in the location and distribution of checkpoints on the parts of the data user and producer. It would not be worthwhile to locate 50 vegetated checkpoints in a fully urbanized county such as Orange County, California—80 non-vegetated checkpoints might be more appropriate. Likewise, projects in areas that are overwhelmingly forested with only a few small towns might support only 20 non-vegetated checkpoints. The general location and distribution of checkpoints should be discussed and agreed upon by the data user and producer as part of the project plan.

C.5 Vertical Checkpoints

Vertical checkpoints need not be well-defined point features; however, they should be placed on smooth, level or gently-sloping terrain away from natural breaks and above-ground features such as curbs, bushes and trees, or in locations like parking lots where cars may be parked during aerial data acquisition. Surveying equipment and methodology should be selected based upon the accuracy needs of the final product; general best practices and guidelines for surveying are addressed in detail in Addendum II.

Vertical checkpoints should be at least two times more accurate than the required accuracy of the elevation data set being tested.

C.6 Horizontal Checkpoints for Elevation Data

Elevation data sets do not always contain the type of well-defined points that are required for horizontal testing according to NSSDA specifications. Specific methods for testing and verifying horizontal accuracies of elevation data sets depend on the technology used and the project design. The specific testing methodologies should be identified in the metadata.

The horizontal accuracy of elevation data generated from photogrammetric processes is the same as the horizontal accuracy achieved for orthophotos or for planimetric maps generated from the same aerial triangulation.

For horizontal accuracy testing of lidar data sets, it is recommended that at least half of the NVA vertical checkpoints should be located at the ends of paint stripes or other point features visible on the lidar intensity image, as this allows them to also serve as horizontal checkpoints. The ends of paint stripes on concrete or asphalt surfaces are normally visible on lidar intensity images, as are 90-degree corners of different reflectivity, e.g., a sidewalk corner adjoining a grass surface. The data producer has the responsibility to establish methodologies appropriate to the technologies used to verify that horizontal accuracies meet the stated requirements.

Testing the horizontal accuracy of lidar data is often difficult, and thus is not always performed. In most cases, users follow the lidar system manufacturer's estimation of horizontal accuracy, as there is no good alternative. Section B.8 provides a formula for estimation of horizontal accuracy as a function of flying height for given sensor parameters, which can be useful for planning lidar data acquisition missions when horizontal accuracy is a concern.

C.7 Testing and Reporting of Product Accuracy

New in Edition 2 of the ASPRS Positional Accuracy Standards for Geospatial Data is the inclusion of checkpoint error in the final computation of the product accuracy. Mapping technologies today can produce data with accuracy that approaches the accuracy of GPS surveys; therefore, two components of error must be accounted for in product testing. The first component of error is caused by the inaccuracy of the internal geometric determination during the aerial triangulation of imagery, or the boresight calibration in lidar processing. The second component of error is introduced by the auxiliary systems used, such as GPS or IMU, or by the instruments used for the ground control and checkpoint surveying. The latter error results in erroneous datum estimation. To accurately compute the product's $RMSE_H$, $RMSE_V$, or $RMSE_{3D}$, both the error from the mathematical modeling and calibration, and the error in the datum estimation due to inaccurate ground control or checkpoints should be considered. The following formula represents the updated and accepted method for computing product accuracy:

$$Horizontal\ Product\ Accuracy\ (RMSE_H) = \sqrt{{RMSE_{H_1}}^2 + {RMSE_{H_2}}^2}$$

$$Vertical\ Product\ Accuracy\ (RMSE_V) = \sqrt{{RMSE_{V_1}}^2 + {RMSE_{V_2}}^2}$$

$$RMSE_{3D} = \sqrt{{RMSE_H}^2 + {RMSE_V}^2}$$

Where:

$RMSE_H$, $RMSE_V$, and $\mathrm{RMSE_{3D}}$ are the product's horizontal, vertical accuracy, and three-dimensional accuracy respectively.

$\mathrm{RMSE_{H_1}}$ and $\mathrm{RMSE_{V_1}}$ are the components of error derived from product fit to the checkpoints.

$\mathrm{RMSE_{H_2}}$ and $\mathrm{RMSE_{V_2}}$ are the components of error associated with the checkpoint surveys.

As an example, compute the vertical accuracy of mobile lidar data set using independent checkpoints according to the above formula, given the following:

- The survey report states that the RTK techniques produced checkpoints with $\mathrm{RMSE_{V_2}}$ = 3-cm.
- When the checkpoints were used to verify the vertical accuracy of the lidar data, the fit of the lidar data to the checkpoints was found to be $\mathrm{RMSE_{V_1}}$ = 1-cm, see section D.1.1 on how to calculate $\mathrm{RMSE_{V_1}}$.

Using the formula above:

$$Vertical\ Product\ Accuracy = \sqrt{1^2 + 3^2} = 3.16\ \mathrm{cm}$$

The correct vertical accuracy of the lidar dataset with respect to the vertical datum is 3.16 cm, rather than the commonly reported value of 1 cm. Additional examples of accuracy computation can be found in Appendix D.

C.7.1 Testing and Reporting Horizontal Accuracy of Digital Orthophotos and Planimetric Maps

For testing and reporting the horizontal accuracy of digital orthophoto and planimetric maps, ASPRS endorses the use of $RMSE_H$ alone, provided that the horizontal errors are normally distributed, the sample size is sufficiently large, and the mean error is sufficiently small. The horizontal accuracy of these products is primarily determined by the accuracy of the aerial triangulation solution. In testing horizontal accuracy, poor point selection or poor measurement techniques can add additional error to the accuracy assessment results. When measuring checkpoints, users should zoom to the highest level possible to minimize pointing errors; ideally, a zoom level that results in sub-pixel pointing accuracy is desirable. If this is not possible or was not practiced, pointing error should be factored into the product accuracy assessment.

Example: Assume that a technician was tasked to assess the horizontal accuracy of an orthophoto of 10-cm GSD. The data was produced to meet the ASPRS horizontal accuracy class of 20-cm. Additionally, assume that, for whatever reason, the technician performed the measurements at a zoom level that introduces 2-pixel pointing error. The “tested to meet” horizontal accuracy as reported by the technician should be as follows:

$$RMSE_H = \sqrt{(20.0)^2 + (2 * 10.0)^2} = 28.28 \text{ cm}$$

In this case, the product accuracy is better than the “tested to meet” accuracy, because measurement error was introduced during the testing process. If the “tested to meet” horizontal accuracy does not meet or exceed the “produced to meet” horizontal accuracy, consideration should be given for this additional source of error before determining whether or not the project has been completed to specification.

C.7.2 Testing and Reporting of Vertical Accuracy of Elevation Data

For testing and reporting the vertical accuracy of digital elevation data, ASPRS endorses the use of $RMSE_V$ alone, provided that the vertical errors are normally distributed, the sample size is sufficiently large, and the mean error is sufficiently small.

VVA should also be computed as $RMSE_V$, but its evaluation should only be based on the reported individual elevation differences (i.e. errors) for each checkpoint. Care should be taken when evaluating skew; skewed results may occur in vegetated areas due to the low density of the lidar point cloud and the degraded quality of GPS surveys under trees. By testing and reporting the VVA separate from the NVA, ASPRS draws a clear distinction between non-vegetated terrain and vegetated terrain where data may be less accurate. These Standards rely primarily on lidar performance in open and unobscured terrain when evaluating data accuracy and quality.

C.8 Low Confidence Areas

For stereo-compiled elevation data sets, photogrammetrists should capture two-dimensional closed polygons for low confidence areas where the bare-earth DTM may not meet the overall data accuracy requirements. Because photogrammetrists cannot see the ground in stereo beneath dense vegetation, in deep shadows, or where the imagery is otherwise obscured, reliable data cannot be collected in those areas. Traditionally, contours within these obscured areas would be published as dashed contour lines.

A compiler should make the determination as to whether the data being digitized is within vegetated or non-vegetated areas. Areas not delineated by an obscure area polygon are assumed to meet accuracy standards. The extent of photogrammetrically-derived obscure area polygons and any assumptions regarding how NVA and VVA accuracies apply to the photogrammetric data set must be clearly documented in the metadata.

Low confidence areas also occur with lidar and IFSAR where heavy vegetation causes poor penetration of the lidar pulse or radar signal. Low confidence areas can be identified with raster analysis based on the following four criteria and converted into 2D polygons for delivery:

- Nominal ground point density (NGPD)
- Search radius to determine average ground point density
- Cell size for the raster analysis
- Minimum size of generalized low confidence areas (minimum mapping unit)

This section describes possible methods for the collection or delineation of low confidence areas in elevation data sets. This list is not meant to be exhaustive; other methodologies currently exist, and additional techniques will certainly emerge in the future. The data producer may use any method they deem suitable, provided the technique is well documented in the metadata.

Table C.2 gives recommendations for low confidence criteria as they relate to vertical accuracy class based on the following assumptions:

- *Nominal Ground Point Density (NGPD)*: Areas with ground point densities less than or equal to ¼ of the recommended nominal pulse density (NPD) are candidates for low confidence areas. For example, a project specification calls for NPD of 1 pt/m^2, but in some vegetated areas, the NGPD is 0.25 pt/m^2. Such areas are good candidates for low confidence polygons.
- *Search Radius*: A search area with radius equal to 3 * NPS for the project (not the low confidence NGPD). This radius is small enough to allow good definition of low density areas while not being so small so as to cause the project to look worse than it actually is.
- *Raster Analysis Cell Size:* To facilitate raster analysis, use a cell size equal to the search radius.
- *Minimum Size for Low Confidence Polygons*: The areas computed with low densities should be aggregated together. Unless specifically requested by clients, structures/buildings and water should be removed from the aggregated low-density polygons, as these features do not represent true low confidence areas. Aggregated polygons greater than or equal to the stated minimum size as provided in Table C.2 should be kept and defined as low confidence polygons. In some cases, too many small areas will "checkerboard" the low confidence areas; in other cases, too many large areas will not adequately delineate low confidence areas. The minimum size of low confidence polygons should be determined by the topography, land cover, and the intended purpose of the maps.

Table C. 2 Low Confidence Area Criteria
Min NPD: Minimum Nominal Point Density, Max NPS: Maximum Nominal Point Spacing
Min NGPD: Minimum Nominal Ground Point Density, Max NGPS: Maximum Nominal Ground Point Spacing

Vertical Accuracy Class	Project Min NPD (pts/m^2) [Max NPS (m)]	Low Confidence Min NGPD (pts/m^2) [Max NGPS (m)]	Cell Size for Computing NGPD (m)	Low Confidence Polygon Minimum Size (acres) [(m^2)]
1-cm	*≥ 20 [≤ 0.22]*	*≥ 5 [≤ 0.45]*	*0.67*	*0.5 [2,000]*
2.5-cm	*≥ 16 [≤ 0.25]*	*≥ 4 [≤ 0.50]*	*0.75*	*1 [4,000]*
5-cm	*≥ 8 [≤ 0.35]*	*≥ 2 [≤ 0.71]*	*1.06*	*2 [8,000]*
10-cm	*≥ 2 [≤ 0.71]*	*≥ 0.5 [≤ 1.41]*	*2.12*	*5 [20,000]*
15-cm	*≥ 1.0 [≤ 1.0]*	*≥ 0.25 [≤ 2.0]*	*3.0*	*5 [20,000]*
20-cm	*≥ 0.5 [≤ 1.4]*	*≥ 0.125 [≤ 2.8]*	*4.24*	*5 [20,000]*
33.3-cm	*≥ 0.25 [≤ 2.0]*	*≥ 0.0625 [≤ 4.0]*	*6.0*	*10 [40,000]*
66.7-cm	*≥ 0.1 [≤ 3.2]*	*≥ 0.025 [≤ 6.3]*	*9.5*	*15 [60,000]*
100-cm	*≥ 0.05 [≤ 4.5]*	*≥ 0.0125 [≤ 8.9]*	*13.4*	*20 [80,000]*
333.3-cm	*≥ 0.01 [≤ 10.0]*	*≥ 0.0025 [≤ 20.0]*	*30.0*	*25 [100,000]*

Acres should be used as the unit of measurement for the low confidence area polygons, as many agencies (USGS, NOAA, USACE, etc.) use acres as the mapping unit for required polygon collection. Approximate square meter equivalents are provided for those whose work is exclusively in the metric system. Smoothing algorithms can be applied to the low confidence polygons, if desired.

There are two distinct types of low confidence areas:

- The first type is identified by the data producer in advance. Areas where acceptable representation of bare earth is expected to be unlikely or impossible should be accounted for ahead of time. No ground control or checkpoints should be located in these areas, and contours, if produced, should be dashed. These areas are exempt from accuracy assessment. Mangroves, swamps, and inundated wetland marshes are prime candidates for this type of delineation.
- The second type occurs in valid VVA areas, such as forests where checkpoints should be surveyed and accuracy assessments ought to be performed, even if they would traditionally be depicted with dashed contours. Such low confidence areas are delineated after classification, and are usually identifiable by notably low-density bare-earth points.

If reliable elevation data in low confidence areas is critical to a project, it is common practice to supplement the remote sensing data with field surveys.

C.9 Erroneous Checkpoints

Occasionally, a checkpoint may be—at no fault of the lidar survey—erroneous or inappropriate for use. Such points may be removed from the accuracy assessment calculation if they meet one or more of the following criteria:

- If it is demonstrated, via pictures and descriptions, that the checkpoint was improperly located, such as a vertical checkpoint that had been placed on steep terrain or within a few meters of a significant breakline that redefines the slope of the area interpolated surrounding the checkpoint.
- If it is demonstrated and documented that the topography has changed significantly between the time the elevation data was acquired and the time the checkpoint was surveyed.
- If (a) the point is included in the survey and accuracy reports, but not the assessment calculation, with pictures and descriptions; (b) reasonable efforts to correct the discrepancy are documented (e.g., rechecked airborne GNSS and IMU data, rechecked point classifications in the area, rechecked the ground checkpoints); and (c) a defensible explanation is provided in the accuracy report for discarding the point.

An explanation that the error exceeds three times the standard deviation (> 3σ) is NOT an acceptable explanation without the proper investigations or justifications as described above.

C.10 Data Internal Precision Assessment

To the greatest extent possible, the location of the test points for determining the data internal precision should meet the following criteria:

- include all overlap areas (sidelap, endlap, and cross flights)
- be evenly distributed throughout the full width and length of each overlap area
- be in non-vegetated areas (clear and open terrain, urban areas, etc.)
- be at least three (3) meters away from any vertical artifact or abrupt change in elevation
- be on uniform slopes
- not include points that are determined to be invalid surface returns, including points with poor geometry

While RMS_{DZ} may be calculated using a set of specific test location points, the maximum difference requirement is not limited to these locations; it applies to all locations within the entire data set that meet the above criteria.

C.11 Interpolation of Elevation Represented Surface for Checkpoint Comparisons

The surface representation of an elevation data set is normally a TIN (Figure C.1) or a raster DEM (Figure C.2).

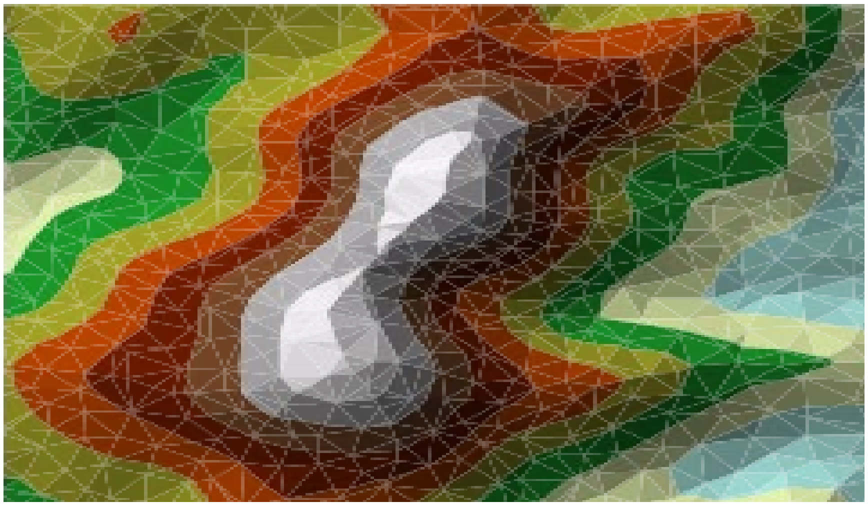

Figure C.1 Topographic Surface Represented as a TIN

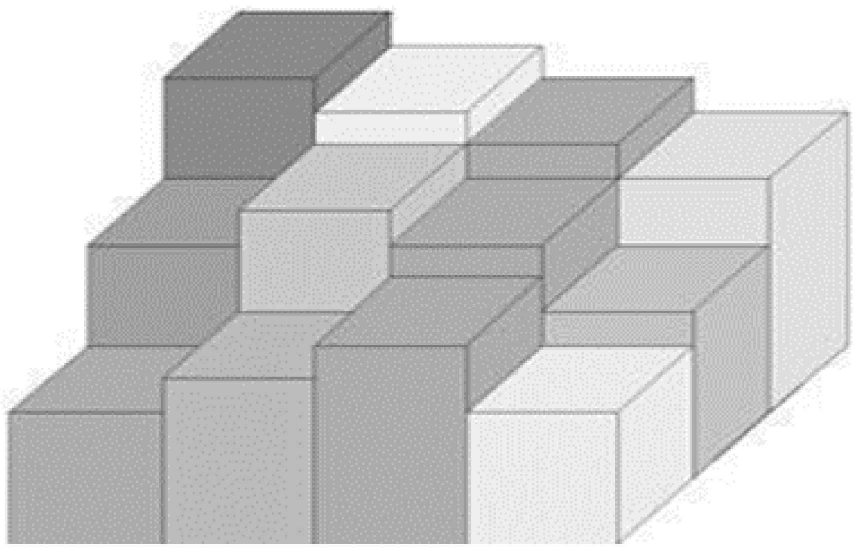

Figure C.2 Topographic Surface Represented as a DEM

Vertical accuracy testing is accomplished by comparing the elevation of the represented surface of the elevation data set to elevations of checkpoints at the horizontal (X, Y) coordinates of the checkpoints. The data set surface is most often represented by a TIN or raster DEM.

Vertical accuracy of point-based elevation data sets should be tested by first creating a TIN from the point-based elevation data set, then comparing the TIN elevations to the checkpoint elevations. TINs should be used to test the vertical accuracy of point-based elevation data sets because it is unlikely a checkpoint will be located at the location of a discrete elevation point. The TIN methodology is commonly used for interpolating elevations from irregularly spaced point data. Other potentially more accurate methods of interpolation exist, and these may be addressed by future versions of these Standards as they become more commonly used and accepted.

Vertical accuracy of raster DEMs should be evaluated by comparing the elevation of the DEM, which is already a continuous surface, to the checkpoint elevations. For most DEM data sets, it is recommended that the elevation of the DEM be determined by extracting the elevation of the pixel that contains the XY coordinates of the checkpoint. However, in some instances, such as when the DEM being tested is at a lower resolution than is typical of global data sets or when the truth data has an area footprint associated with it rather than a single XY coordinate, it may be better to use interpolation methods to determine the elevation of the DEM data set.

Vendors should seek approval from clients if methods other than extraction are to be used to determine elevation values of the DEM data set. Vertical accuracy testing methods listed in the metadata and the reports should state if elevation values were extracted from the tested data set at the XY location of the checkpoints, or if further interpolation was used after the creation of the tested surface (TIN or raster) to determine the elevation of the tested data set. If further interpolation was used, the interpolation method and full process used should be detailed accordingly.

APPENDIX D — ACCURACY STATISTICS AND EXAMPLE (NORMATIVE)

D.1 Reporting Accuracy Statistics

The National Standard for Spatial Data Accuracy (NSSDA) documents the equations for the computation of $RMSE_X$, $RMSE_Y$, $RMSE_R$ and $RMSE_Z$, as well as horizontal (radial) and vertical accuracies at the 95% confidence levels—$Accuracy_R$ and $Accuracy_Z$, respectively. These statistics assume that errors approximate a normal error distribution and that the mean error is small relative to the target accuracy. The ASPRS Positional Accuracy Standards for Digital Geospatial Data reporting methodology is based on RMSE alone, and thus differs from the NSSDA reporting methodology. Additionally, these Standards include error inherited from ground control and checkpoints in the computed final product accuracy, as discussed in Appendix C.

D.1.1 Accuracy Computations

For the purposes of demonstration, suppose you must use five checkpoints to verify the final horizontal and vertical accuracy for a data set (this is fewer than the 30 checkpoints required by these Standards—the example uses fewer for the sake of brevity) according to this ASPRS accuracy Standards.

Table D.1 provides the map-derived coordinates and the surveyed coordinates for the five points. The table also shows the computed accuracy and other relevant statistics. In this abbreviated example, the data are intended to meet a target horizontal accuracy class of $RMSE_H$ = 15-cm and a target vertical accuracy class of $RMSE_V$ = 10-cm.

Table D.1 Accuracy Statistics for Example Data

Point ID	Map-derived Values			Surveyed Checkpoints Values			Residuals (Errors)		
	Easting (E)	Northing (N)	Elevation (Z)	Easting (E)	Northing (N)	Elevation (Z)	ΔE (Easting)	ΔN (Northing)	ΔZ (Elevation)
	meter	meter	meter	meter	meter	meter	meter	meter	meter
GCP1	359584.394	5142449.934	477.127	359584.534	5142450.004	477.198	-0.140	-0.070	-0.071
GCP2	359872.190	5147939.180	412.406	359872.290	5147939.280	412.396	-0.100	-0.100	0.010
GCP3	359893.089	5136979.824	487.292	359893.072	5136979.894	487.190	0.017	-0.070	0.102
GCP4	359927.194	5151084.129	393.591	359927.264	5151083.979	393.691	-0.070	0.150	-0.100
GCP5	372737.074	5151675.999	451.305	372736.944	5151675.879	451.218	0.130	0.120	0.087
					Number of check points		5	5	5
					Mean Error (m)		-0.033	0.006	0.006
					Standard Deviation (m)		0.108	0.119	0.091
					RMSE (m)		0.102	0.106	0.081
					Fit to Checkpoints $RMSE_{H1}$ (m)		0.147	$RMSE_H = \sqrt{RMSE_E^2 + RMSE_N^2}$	
					Fit to Checkpoints $RMSE_{V1}$ (m)		0.081		

Computation of Horizontal, Vertical, and Three-Dimensional Accuracy:

1. Compute the Root Mean Square Error Values:

$$RMSE_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{i(map)} - x_{i(surveyed)})^2}$$

where:

$x_{i(map)}$ is the coordinate in the specified direction of the i^{th} checkpoint in the data set,

$x_{i(surveyed)}$ is the coordinate in the specified direction of the i^{th} checkpoint in the independent source of higher accuracy,

n is the number of checkpoints tested,

and *i* is an integer ranging from 1 to *n.*

$$RMSE_x = \sqrt{\frac{(-0.140)^2+(-0.100)^2+(0.017)^2+(-0.070)^2+(0.130)^2}{5}} = 0.102 \text{ m}$$

$$RMSE_y = \sqrt{\frac{(-0.070)^2+(-0.100)^2+(-0.070)^2+(0.150)^2+(0.120)^2}{5}} = 0.107 \text{ m}$$

$$RMSE_{H_1} = \sqrt{RMSE_x{}^2 + RMSE_y{}^2}$$

$$RMSE_{H_1} = \sqrt{(0.102)^2 + (0.107)^2} = 0.147 \text{ m}$$

$$RMSE_{V_1} = \sqrt{\frac{(-0.071)^2+(0.010)^2+(0.102)^2+(-0.100)^2+(0.087)^2}{5}} = 0.081 \text{ m}$$

2. Compute the Final Accuracy Values:

To complete the accuracy computations, let us assume that the checkpoint report submitted by the surveyor states that the field survey was conducted using an RTK-GPS-based technique to an accuracy of:

Horizontal Accuracy $RMSE_{H_2}$ = 1.9 cm or 0.019 m

Vertical Accuracy $RMSE_{V_2}$ = 2.23 cm or 0.022 m

The final horizontal and vertical accuracy should be computed as follows:

$$RMSE_H = \sqrt{RMSE_{H_1}{}^2 + RMSE_{H_2}{}^2} = \sqrt{(0.147)^2 + (0.019)^2} = 0.148 \text{ m } (< 15 \text{ cm})$$

$$RMSE_V = \sqrt{RMSE_{V_1}{}^2 + RMSE_{V_2}{}^2} = \sqrt{(0.081)^2 + (0.022)^2} = 0.083 \text{ m } (< 10 \text{ cm})$$

Similarly, the three-dimensional positional accuracy can be computed using the following formula:

$$RMSE_{3D} = \sqrt{RMSE_H{}^2 + RMSE_V{}^2}$$

Therefore,

$$RMSE_{3D} = \sqrt{0.148^2 + 0.083^2} = 0.170 \text{ m}$$

Based on the computed horizontal and vertical accuracy numbers above, the product is meeting the specified horizontal and vertical accuracies of 15-cm and 10-cm, respectively.

Computation of Mean Errors in X, Y, and Z:

$$\underline{x} = \frac{1}{(n)}\sum_{i=1}^{n} x_i$$

where:

x_i is the *i^th^* error in the specified direction,

n is the number of checkpoints tested,

i is an integer ranging from 1 to *n.*

Mean error in Easting: $\bar{x} = \frac{-0.140-0.100+0.017-0.070+0.130}{5} = \text{-}0.033 \text{ m}$

Mean error in Northing: $\bar{y} = \frac{-0.070-0.100-0.070+0.150+0.120}{5} = 0.006 \text{ m}$

Mean error in Elevation: $\bar{z} = \frac{-0.070+0.010+0.102-0.100+0.087}{5} = 0.006 \text{ m}$

Computation of Sample Standard Deviation:

$$s_x = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}\left(x_i - \underline{x}\right)^2}$$

where:

x_i is the *i^th^* error in the specified direction,

$\underline{x}$ is the mean error in the specified direction,

n is the number of checkpoints tested,

i is an integer ranging from 1 to *n.*

Sample Standard Deviation in Easting:

$$s_x = \sqrt{\frac{\left(-0.140-(-0.033)\right)^2+\left(-0.100-(-0.033)\right)^2+\left(0.017-(-0.033)\right)^2+\left(-0.070-(-0.033)\right)^2+\left(0.130-(-0.033)\right)^2}{(5-1)}} = 0.108 \text{ m}$$

Sample Standard Deviation in Northing:

$$s_y = \sqrt{\frac{(-0.070-0.006)^2+(-0.100-0.006)^2+(-0.070-0.006)^2+(0.150-0.006)^2+(0.120-0.006)^2}{(5-1)}} = 0.119 \text{ m}$$

Sample Standard Deviation in Elevation:

$$s_z = \sqrt{\frac{(-0.071-0.006)^2+(0.010-0.006)^2+(0.102-0.006)^2+(-0.100-0.006)^2+(0.087-0.006)^2}{(5-1)}} = 0.091 \text{ m}$$

Computation of Population Standard Deviation:

$$s_x = \sqrt{\frac{1}{(n)}\sum_{i=1}^{n}\left(x_i - \underline{x}\right)^2}$$

where:

x_i is the *i*th error in the specified direction,

$\underline{x}$ is the mean error in the specified direction,

n is the number of checkpoints tested,

i is an integer ranging from 1 to *n.*

Sample Standard Deviation in Easting:

$$s_x = \sqrt{\frac{\left(-0.140-(-0.033)\right)^2+\left(-0.100-(-0.033)\right)^2+\left(0.017-(-0.033)\right)^2+\left(-0.070-(-0.033)\right)^2+\left(0.130-(-0.033)\right)^2}{(5)}} = 0.096 \text{ m}$$

Sample Standard Deviation in Northing:

$$s_y = \sqrt{\frac{(-0.070-0.006)^2+(-0.100-0.006)^2+(-0.070-0.006)^2+(0.150-0.006)^2+(0.120-0.006)^2}{(5)}} = 0.106 \text{ m}$$

Sample Standard Deviation in Elevation:

$$s_z = \sqrt{\frac{(-0.071-0.006)^2+(0.010-0.006)^2+(0.102-0.006)^2+(-0.100-0.006)^2+(0.087-0.006)^2}{(5)}} = 0.081 \text{ m}$$

ADDENDUM I: GENERAL BEST PRACTICES AND GUIDELINES

CONTENTS

FIGURES

TABLES

This addendum contains best practices and guidelines for all users of the ASPRS Positional Accuracy Standards for Digital Geospatial Data.

SECTION A: REPORTING NOTES FOR DELIVERED PRODUCTS

Contributor: Michael Zoltek, GPI Geospatial, Inc.

The ASPRS Positional Accuracy Standards for Digital Geospatial Data encourage truth in reporting when delivering geospatial products or services. This section provides examples of reporting notes to accompany delivered products. Subsections provide specific reporting guidelines for various categories of deliverables.

All accuracies should be reported as "tested to meet" or "produced to meet" in accordance with ASPRS Positional Accuracy Standard for Digital Geospatial Data, Section 7.15. To provide clients with the required metadata to support the proper use of geospatial deliverables, it is recommended that the following notes be included in reports for the various types of deliverables described herein:

A.1 Notes Related to Geospatial Deliverables in General

1. The elevation data provided was ***tested to meet a vertical accuracy of xxx (units) RMSE, using xxx checkpoints*** in clear unobscured areas, to support the generation of a ***x-(units) contour interval*****.**
2. The delivered elevation data is the source for any delivered derivative products (e.g., contours). The project's delivered elevation data should be utilized as the sole source for creating any additional derivative products or subsequent computations.
3. This map was produced by photogrammetric methods using: (select all that apply)
    a. Aerial lidar
    b. Aerial photogrammetry
4. The following sensors were utilized to collect the data for this project:
    a. Aerial imagery sensor
        i. Sensor make
        ii. Sensor model
        iii. Calibration date
    b. Aerial lidar sensor
        i. Sensor make
        ii. Sensor model
        iii. Calibration date
5. The following software products were utilized during the creation of the deliverables:
    a. Trajectory processing
    b. Lidar data processing
        i. Calibration
        ii. Classification
        iii. Data extraction
        iv. Data validation

   c. Name of Imagery Processing Software Used:
      i. Aerial triangulation
      ii. Orthomosaic production
      iii. Stereo compilation
      iv. Data validation
   d. Name of software used for compilation:
      i. Stereo viewing/extraction
      ii. Lidar point cloud extraction
      iii. Data validation
6. Ground control and/or checkpoints were provided by:
   a. Firm name, address, phone number, and license number
   b. Signing surveyor name and license number
7. Ground control and/or checkpoint coordinate values are as follows:
   a. Provide coordinates in local state plane or client-requested coordinate system.
   b. ALWAYS provide coordinates in lat/long/ellipsoid height to allow for validation of any coordinate transformations or reprojections.
8. GPS positional data was observed on/between the dates of ***mo/day/year*** and ***mo/day/year*** utilizing a ***make/model*** receiver. The grid coordinates of the Fixed Station(s) shown were derived using a ***describe network*** (e.g., Local Static Control, VRS network of CORS stations) referenced to ***datum (year), epoch (year), geoid (year)***.
9. The positional accuracy of the GPS vectors is: ***Horizontal H.HH (units), Vertical V.VV (units), Combined Grid Factor: 0.xxxxxxxx centered on Fixed Station xxxx as shown hereon***.
10. Accuracies of horizontal control points are reported as being ***xxx (units) RMSE with a standard deviation of xxx (units)***. Individual point statistics can be found in ***Appendix X.*** A Coordinate Quality report can be utilized to provide individual point statistics.
11. Accuracies of vertical control points are reported as being ***xxx (units) RMSE with a standard deviation of xxx (units)***. Individual point statistics can be found in ***Appendix X.***
12. Delivered products are referenced to the following spatial reference system:
    a. Horizontal datum with epoch
    b. Vertical datum with epoch and reference geoid
    c. Projection (UTM, State Plane, etc.)

A.2 Notes Related to Aerial Imagery Deliverables

1. Date of Aerial Imagery Capture, ***Month Day, Year***.
2. The imagery was ***collected at xxx (units) nominal GSD*** to support the production of orthorectified digital maps with ***xxx (units) GSD***.
3. The accuracy of aerial triangulation, which was performed ***using xxx ground control points and XYZ software***, was found to be ***$RMSE_H$ = xxx, $RMSE_V$ = yyy***. If aerial triangulation was not performed and the direct-georeferencing approach used instead, the accuracy of the IMU orientation angle, role, pitch, and heading alongside the final product accuracy (as verified by checkpoints or ground control points, if available) should be reported.

4. Describe the source of the elevation surface utilized to produce the orthophotography, as well as any modifications made to the orthophotography by the consultant.

5. This imagery mapping product was ***tested to meet a horizontal accuracy of xxx (units) $RMSE_H$ using xxx checkpoints.***

6. If a client specifies a legacy standard, add a comparison to the legacy equivalent, e.g., ***"which is equivalent to the ASPRS Accuracy Standards for Large-Scale Maps (1990) ASPRS Class 1 at a map scale of 1:2400."***

7. Compiled vector features ***have been tested to meet a horizontal accuracy of x.xx (units) RMSE, using xxx checkpoints*** in clear unobscured areas. Planimetric features in areas delineated as "visually obscured" may not adhere to this accuracy.

8. Compiled vector features ***have been tested to meet a vertical accuracy of x.xx (units) RMSE, using xxx checkpoints*** in clear unobscured areas. Planimetric features that lie in areas delineated as "visually obscured" may not adhere to this accuracy.

9. Report sequence of orientation angles: ***The exterior orientation angles rotation sequence is:***
    a. Omega, phi, kappa
    b. Other sequences

10. Report camera integration on aircraft: ***The camera was oriented with the image positive y-axis in the direction of flight***.

A.3 Notes Related to Aerial Lidar Deliverables

1. Date of Lidar Capture, ***Month Day, Year***.
2. Lidar data was collected nominally at ***xxx points per square meter (or xxx points per square foot)*** resulting in an equivalent ***xxx cm (or xxx foot) nominal point spacing***.
3. This lidar mapping product ***was tested to meet a vertical accuracy of xxx (units) $RMSE_V$ using xxx checkpoints in non-vegetated terrain***.

SECTION B: ERROR NORMALITY TESTS

Contributor: Dr. Christopher E. Parrish, Oregon State University

B.1 Creating the Normality Test

Following an accuracy test, it is considered good practice to assess and report whether the errors[6] are normally distributed (i.e., whether they are well modeled by a Gaussian distribution). This assessment can provide context to the accuracy test results, and, in some cases, may help detect sources of error or other issues in the project framework. For example, if the error distribution is non-normal, this could indicate the presence of blunders or large systematic errors, which should be investigated further.

[6] In keeping with the terminology convention used throughout these Standards, in this addendum, we use the term "errors" where, strictly-speaking, we mean "residuals."

The first step in testing the normality of the error distribution is a visual test, which is performed by plotting and inspecting a histogram of errors. Histogram plotting functions are available in any number of spreadsheet software packages and programming languages. An example of an error histogram is shown in Figure I.B.1. This example is from testing the accuracy of an airborne lidar point cloud covering a portion of the Oregon State University (OSU) campus using 87 field-surveyed checkpoints. The checkpoints were surveyed using a combination of RTK GNSS and total station observations, with a least squares adjustment subsequently performed using a commercial software package.

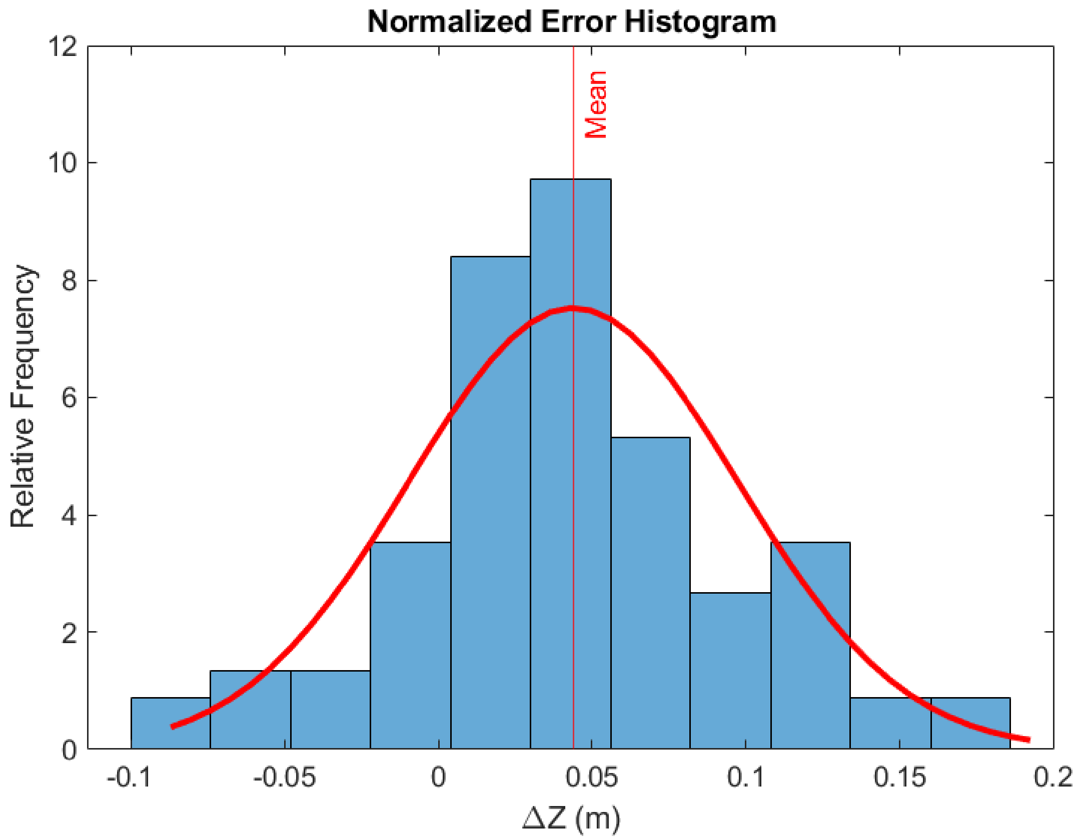

Figure I.B.1 Example of an error histogram.
The orange curve is a fitted Gaussian distribution. The vertical line denotes the location of the mean. This histogram has been normalized, such that the area under the plot is equal to one.

Important items to look for in the visual test include:

1. The mean should be near zero, as a large (positive or negative) mean indicates the presence of bias in the data.
2. There should be no spikes far from the mean, as these would indicate the presence of outliers.
3. The distribution should be symmetric about the mean (not positively or negatively skewed).
4. The general shape of the error histogram should approximate the “bell-shaped curve” of the normal (Gaussian) distribution.

Following the visual assessment of the error histogram, the next step is to perform a quantitative normality test. Lilliefors test for normality is recommended. The Lilliefors test is based on, but includes improvements to, the well-known Kolmogorov-Smirnov (K-S) test. Importantly, the Lilliefors test is available as a built-in function in commercially-available spreadsheet software packages and programming languages (Figure I.B.2). Another well-known and widely-used normality test is the Shapiro-Wilk (S-W) test.

```
%% Perform Lilliefors test for normality
h = lillietest(deltaZs);
if h == 0
    disp('DeltaZs PASS Lilliefors test for normality')
elseif h == 1
    disp('DeltaZs FAIL Lilliefors test for normality')
else
    disp('Warning: check format of input data')
end
```

Figure I.B.2 Lilliefors test for normality implemented in MATLAB.

When analyzing the error histogram shown in Figure I.B.1, visual analysis confirms that the error distribution looks reasonable, although the mean of 4 cm indicates a positive bias (i.e., the lidar data are, on average, 4 cm too high with respect to the checkpoints), and the distribution is slightly positively skewed. Visual assessment indicates a lack of outliers. This error distribution passes Lilliefors test for normality. However, this test data set does not satisfy the criterion of mean error, μ < 25% of the RMSE, which is discussed Section 7.2 of the ASPRS Positional Accuracy Standards for Digital Geospatial Data. In this case, the mean error is 64% of the RMSE, indicating that the RMSE is dominated by a large bias. This bias should be investigated further.

B.2 Interpreting the Normality Test

There are many reasons why errors may not be normally distributed, and it is important to recognize that failing a normality test (the visual and/or quantitative portion) does not necessarily indicate a problem with the data, the checkpoints, or the test. However, assessing the results of the normality test can often help uncover mistakes or other issues made during testing.

For example, say a data producer finds a number of errors that fail a normality test. The data producer then conducts a follow-up investigation that reveals the errors were caused by incorrect boresight calibration parameters being applied while processing the data. In this hypothetical example, perhaps the original data met the required accuracy, as specified in the contract, but reprocessing the data with the correct boresight parameters applied leads to even better accuracy and normally-distributed errors.

Or, for another example, say assessment of the normality test results leads to the discovery of one or more checkpoints whose corresponding residuals exceed three standard deviations from the mean. While it is improper and in violation of these Standards to exclude checkpoints from the accuracy test simply because their corresponding errors are large (without additional justification), further analysis of the checkpoint or checkpoints in question may provide important insight. Perhaps, in a particular airborne lidar project, there was a two-week time gap between the checkpoint survey and aerial survey, and it is discovered that a parking lot, in which two of the checkpoints were located, was repaved in this interval.

As one final example, it might be discovered that one of the checkpoints, which was surveyed with RTK GNSS, was near a tall chain-link fence, and subsequent analysis of the GNSS data may indicate that the checkpoint coordinates were affected by poor satellite geometry and multipath errors.

In all of these examples, if the accuracy test is repeated with these checkpoints withheld, the accuracy report must clearly state exactly which checkpoints were withheld, and it must provide a detailed justification.

B.3 Reporting the Normality Test

It is recommended that the error histogram be included and discussed in the accuracy report, so that it may provide context to the reported accuracy statistics. The accuracy report should state the type of normality test performed (e.g., Lilliefors test or Shapiro-Wilk test). If the error distribution fails the normality test (visual and/or quantitative portion), this should be stated and discussed in the report, including any findings from subsequent analysis, such as in the examples given above.

SECTION C: LIDAR DATA QUALITY VERSUS POSITIONAL ACCURACY

Contributor: Dr. Qassim Abdullah, Woolpert, Inc.

When modelling terrain with lidar, it is important to be aware of the difference between elevation data quality and positional accuracy. In many instances, users of lidar data focus solely on point cloud accuracy as specified by sensor manufacturers, but an accurate lidar point cloud does not necessarily result in accurate modeling of the terrain, nor will it create accurate volumetric calculations: elevation data must also faithfully represent the terrain detail. Therefore, users should also consider point density as it relates to terrain roughness or smoothness, as this is an equally important aspect of accurate terrain modelling.

Terrain modeling methodologies (e.g., polygon-based Regular Triangulated Network (RTNs) or Triangulated Irregular Network (TIN) versus Voxel-based Network) also affect the terrain model quality. Terrain analysis is sensitive to whether the software represents the point cloud as a TIN, a gridded surface, or an RTN. Methods that involve gridding the data are sensitive to grid cell size (post spacing); lidar point density is an important factor when choosing grid cell size.

Figure I.C.1 illustrates the relationship between terrain roughness and point density. While the point cloud in this example may have a vertical accuracy of $RMSE_V$ = 10-cm, TIN interpolation based on surrounding areas of low point density places the vertical position of point A at point A', resulting in a vertical error of 2 meters in this example. The remedy is to obtain the point cloud at a higher density so that it more accurately represents the terrain detail. Attempting to use a low-density point cloud to represent terrain with high frequencies of undulation will result in inaccurate volume estimations, regardless of what software or modeling algorithms are used. Smoother terrain may be adequately represented with a lower density point cloud. Very smooth or flat terrain can be accurately modeled using a point cloud with nominal post spacing (NPS) of a few meters or coarser.

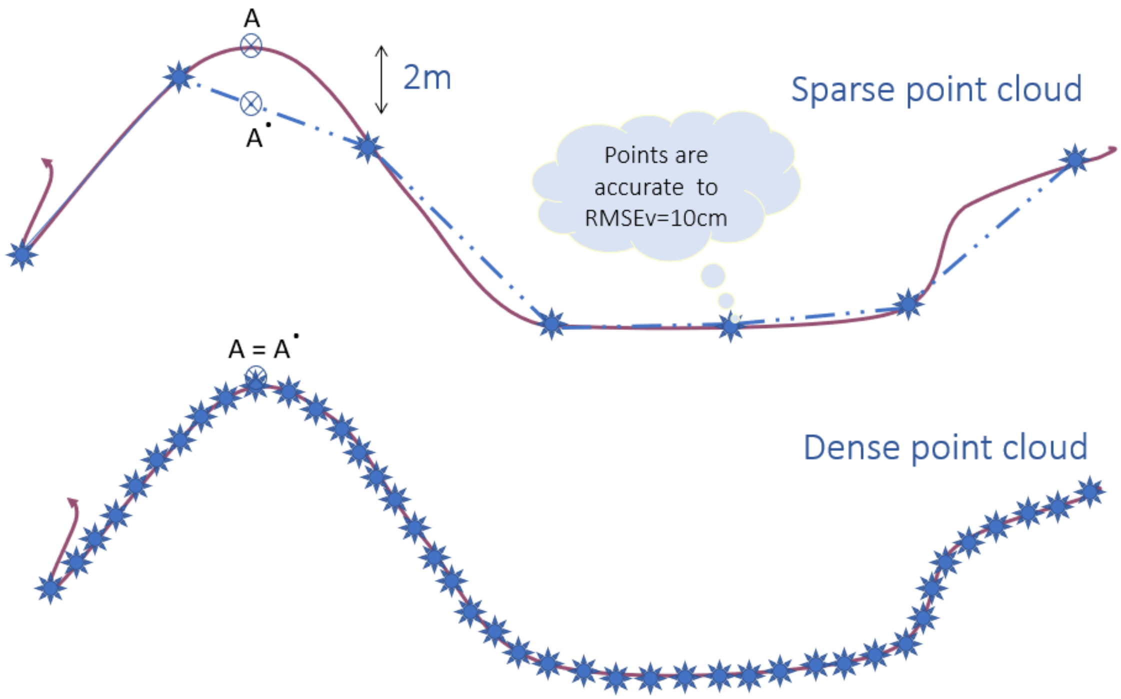

Figure I.C.3 Terrain Model Quality as a Function of Point Density and Vertical Accuracy

The Nyquist-Shannon sampling theorem, which is well-known and widely used in signal processing, may be used to determine the point density required to accurately represent the project terrain. According to the Nyquist-Shannon sampling theorem, if a signal x(t) contains no frequencies higher than B Hz, then a sampling rate of greater than 2B samples per second (or 2B Hz) will be needed in order to reconstruct the original signal without aliasing.

For example, let us assume that the undulation rate of the terrain represents the highest frequency of the signal to be modelled, and the nominal point spacing represents the sampling rate needed to model the terrain without aliasing. If we want to accurately model rocky terrain where the spikes caused by these rocks appear every 30 cm on average, the nominal point spacing of the lidar data used to model this terrain should be less than 15 cm.

SECTION D: LIDAR SYSTEM CLASSIFICATION AND GROUPING

Contributors:

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ASPRS UAS Division

D.1 Introduction

Mapping professionals new to lidar technology generally find themselves faced with the challenge of selecting the right system for their needs from the many lidar systems available on the market today. Due to the wide range of price and performance across various key subsystems (laser rangefinders, scanner types, inertial navigation and positioning systems etc.), lidar systems may vary greatly from each other. Specific sensor designs may not fit easily into a category, or they may straddle different group definitions or technical performance envelopes. This section is intended to provide a broad overview of the major technical differences between designs, for professionals who are unfamiliar with lidar technology, but who may be considering incorporating it into their projects in the future.

D.2 **Lidar System Performance**

The overall performance of a UAS-based lidar system is determined by the technical specifications of the core subsystems, most critically the laser rangefinder (the lidar subsystem), the scanner, and the navigation subsystem (which is responsible for the position and orientation of the sensor during flight). As with any complex system design, overall achievable accuracy is determined by the total combined error budget of all subsystems. When optimizing the price/performance curve for a sensor design, it is important to match the performance of each subsystem against the component price and against each other. A low-end IMU may not be able to make use of a high-performing lidar component with exceptional range performance and very low shot noise. Similarly, using the highest accuracy positioning solution available on the market may not improve the inherent limitations of using low-cost, low-spec lidar. When considering the design of the UAS lidar system, care should be taken to ensure subsystems are not mismatched in terms of technical specifications. Technical specifications regarding achievable performance should always be based on the overall system performance, not on the individual specifications of the various subsystems.

D.3 Lidar System Classification

Since lidar technology is still evolving, the geospatial mapping industry has not yet developed a mature classification system to categorize the different lidar systems available on the market. The following group designation system is based around payload weight and/or primary platforms used, and are intended as guidelines only. Please note that some sensor designs may not easily fit into a specific grouping.

Group 0 – Consumer-Grade Lidar

Consumer products such as iPhones are starting to include lidar scanning as a function alongside their built-in digital cameras. Lower-cost, lower-performance “2D” lidars or basic rangefinders are becoming more common in robotic vision applications such as autonomous vacuum cleaners. While the embedded lidar technology in consumer products is improving, such consumer-grade lidar systems are not considered suitable for professional aerial mapping applications.

Group 1 – UAS Mounted Lidar < 2.5 kg Payloads

Starting in approximately 2010, the automotive industry has created a demand for compact, lower-priced UAS lidar systems for use in self-driving vehicles. The size, weight, and power of these compact lidar systems, when paired with lower-cost position and orientation systems, makes them suitable for many remote sensing applications, such as by UAS for aerial mapping, by vehicle for mobile mapping, or by backpack for personal/on-foot mapping. The range of options in this group is varied and spans from older opto-mechanical designs with spinning mirrors to newer all solid-state designs with no moving parts. Their low cost compared to more traditional lidar systems ($1,000s to $100,000 USD vs. $500,000s USD and up for traditional aerial lidar systems), as well as their compact size and low power requirements, are the primary benefit of these lidars. Due to the range of options in this group, it is difficult to generalize, but these systems tend to have all or most of the following characteristics:

- Single wavelength operation in the near IR around 900 nm.
- Multi-channel designs typically featuring 8x, 16x or 32x individual laser transmitters. Designs with 64x or 128x channels are less common, but may be available.
- 360-degree rotating mirrors for scanning with a fixed forward/backward spread of 10-20 degrees due to the multiple channels (a fan of beams).
- Fixed fields of view for solid-state imagers.
- Range performance to 20% reflectivity targets is typically in the 50–300 m range, due to the lower peak pulse power and reduced sensitivity of the receiver designs compared to lidars designed for higher-altitude operations.
- Detectability (percent of pulses return a specified range to specified reflectivity target) better than 50%, with most newer designs rating better than 90%.
- Asymmetrical beams with divergences in the 1–3 mrad (or higher) range and with a major and minor axis, resulting in an elliptical beam pattern on the ground.
- Higher shot-to-shot noise (higher range error), resulting in greater peak-to-peak noise or “fuzziness” on hard surfaces.
- Multiple returns on most, but not all, systems, with most systems capturing 2–5 returns per pulse.
- Intensity (return pulse amplitude) captured as 8- or 12-bit values, typically not normalized to pulse energy.
- Traditional time-of-flight (ToF) return pulse detection method.
- Achievable vertical accuracy ($RMSE_z$) compared to control (network accuracy) better than 10-cm, with most systems capable of better than 5-cm given a good GNSS position solution and a compatible IMU for orientation.
- Precision of 3.0–7.0 cm over hard surfaces (single pass, 1σ deviation) with peak-to-peak noise of 10–20 cm over the same surface (before any smoothing of the point cloud).
- Integration with a compatible position and orientation system (POS) that provides approximate post-processed position accuracy of 0.02–0.05 m, 0.08° heading, 0.025° pitch/roll.

Group 2 – UAS-Mounted Lidar < 10.0 kg Payloads

Moving up in price/performance from Group 1 typically involves moving to systems integrated with lidars purpose-built for long range mapping applications paired with higher-accuracy IMUs for better angular (orientation) measurements. This typically increases the payload weight and power requirements, requiring a drone with a greater lift capacity than would typically be used in Group 1 systems. There are a range of medium-lift commercial drones capable of carrying payloads up to 10 kg for extended durations, making them very suitable for mapping applications. Positional accuracy via GNSS tends to remain the same as for the prior group. With longer-range performance, the highest performing systems in this group are also capable of operating from fixed-wing or helicopter platforms flying at low altitudes. These systems are characterized by all or some of the following characteristics, relative to Group 1:

- Single wavelength operation on most systems in the 1.0–1.5 micron range. Dual (IR/Green) wavelength options available in some models for bathymetric applications.
- Range performance to 20% reflectivity targets is typically in the 100–1,000 m range, due to higher peak pulse power from the laser and more sensitive receiver designs.
- Detectability (percent of pulses return a specified range to specified reflectivity target) better than 95%, with most newer designs reaching better than 99%.
- Improved beam quality with symmetrical beam shapes and beam divergences in the 0.3–0.7 mrad range.
- Single channel (single transmitted beam) design for many systems, though dual and triple beam designs are becoming more common. Some quad-channel designs available for mobile mapping applications.
- Traditional time-of-flight (ToF) return pulse or full waveform digitization detection methods.
- Geiger-mode and single photon receiver designs may be available in some models.
- Multiple returns, up to 15 in some designs. Last-pulse and multiple last-pulse logic is standard.
- Intensity captured up to 16-bit values, on some designs normalized to outgoing pulse energy to provide more uniform reflectance measurements.
- 360-degree rotating mirrors or oscillating mirrors (side-to-side) for scanning. Oscillating mirrors provide greater sampling rates for the same PRR by keeping all pulses in the effective field of view.
- Achievable vertical accuracy ($RMSE_z$) compared to control (network accuracy) better than 5-cm, with most systems capable of better than 2.5-cm given a good GNSS position solution and a compatible IMU for orientation.
- Precision of 0.5–1.5 cm over hard surfaces (single pass, 1σ deviation) with peak-to-peak noise of 5–10 cm (before any smoothing of the point cloud).
- Integrated with a compatible position and orientation system (POS) that provides approximate post-processed position accuracy of 0.02–0.05 m, 0.035° heading, 0.015° pitch/roll.

Group 3 – Manned Aircraft Mounted Lidar

This group covers traditional aerial lidar systems deployed on fixed-wing and helicopter platforms. These are the established airborne lidar sensor designs that have been available commercially for 30 years.

Built around time-of-flight measurements with purpose-built lidars and scanners, they use high-accuracy positioning and orientation subsystems to allow accurate mapping from ranges of 3,000 m or more. They are optimized for wide area collection and high-density corridor mapping from fixed-wing survey aircraft or helicopter platforms. In addition to time-of-flight, Geiger-mode and single-photon designs are also utilized to achieve the greatest efficiency possible when mapping large regions. This group also includes most bathymetric lidar systems.

Group 4 – SLAM-Based Mapping Systems (Various Platforms)

Simultaneous Localization and Mapping (SLAM) sensor designs have become common in mapping applications over the past two decades. SLAM is a technique used in vision systems to allow a sensor to simultaneously map its surroundings in 3D space and locate itself accurately in that space. SLAM is used for real-time mapping, path/route planning, and obstacle avoidance in various applications. SLAM is a general term, and there are a variety of different algorithms and implementation approaches that can all be considered “SLAM” systems. The term “visual SLAM” refers to the use of SLAM with imagery from on-board cameras, while “lidar (or laser) SLAM” refers to the use of lidar as the primary on-board sensor feeding the SLAM algorithm. Visual SLAM is more common in consumer appliances such as robotic vacuums, or in controlled environments such as warehouses, whereas lidar SLAM is the more common implementation in mapping applications. The commercial development of SLAM sensors has been driven by the development of efficient SLAM algorithms and the fall in cost of key sensors such as digital cameras and lidars, along with the overall increase in on-board computing power available to process the SLAM algorithms from the sensor data in real-time.

A common characteristic of all SLAM-based mapping systems is that they work without needing a GNSS positioning solution, unlike traditional mapping lidars and UAS lidar systems, allowing SLAM-based mapping systems to work in GNSS-denied environments such as underground areas, indoors, or in confined spaces. Instead, positioning is provided by identifying and tracking targets and landmarks in the local environment as the system moves through the space. Tying landmarks to known locations in a spatial reference frame allows for absolute positioning of the resulting data. With enough identifiable targets in the scene, achievable positional accuracy is similar to a post-processed kinematic (PPK) survey-grade L1/L2 GNSS solution. For mapping purposes, this can generally be taken as 5 cm or better. Note that both SLAM and GNSS have requirements that mirror each other; GNSS systems need a good view of satellites in the sky, while SLAM systems need a good view of 3D features or set targets on the ground. Both will degrade in positional accuracy and ultimately fail if their respective requirements are not met. Hybrid sensor designs using both GNSS and SLAM positioning are being investigated, but these are not generally available commercially as of 2023.

Since a SLAM system maps its environment as it moves, it can be used to map any 3D space that has suitable geometries for landmark and target identification. SLAM-based systems are being used more and more often to map outdoor spaces, sometimes in conjunction with UAS lidar mapping. However, there are limitations to mapping with SLAM sensors:

- SLAM systems need a feature-rich environment to identify tracking targets and landmarks for localization, so they may have issues in excessively monotonous environments, such as the top of a continuous canopy or long stretches of empty corridors. Additional control targets may need to be added for effective mapping in such environments.

- Scaling to map large outdoor areas is less efficient with SLAM than a traditional GNSS approach. SLAM collection efficiency usually decreases with area, while GNSS collection efficiency usually increases.
- Localization errors may accumulate over time. Appropriate steps should be taken in the algorithm and data processing to minimize loop closure problems.

For indoor (GNSS-denied, confined spaces) mapping projects, SLAM-based sensors offer the best approach currently available for rapid, accurate mapping data collection. For outdoor (open-sky) mapping projects, factors such as the availability of suitable identifiable targets and landmarks in the area, the efficiency of collection, and the field logistics will affect how effective a SLAM-based mapping system will be over a GNSS system.

D.4 Lidar System Cost

There is a competitive commercial market for the sales and support of UAS lidar systems, with multiple vendors for both GNSS-based and SLAM-based systems designed for mapping applications. System integrators typically provide an integrated payload with a lidar, GNSS/IMU position and orientation subsystem (or a SLAM-based design), on-board processor, data recorder, flight planning software, and data post-processing software. The key subsystems can be sourced from third-party vendors, who may also offer integrated mapping systems themselves (e.g. Riegl, Teledyne, Hexagone) or who may only sell components to integrators (e.g. Hesai, Velodyne, Livox). It is increasingly common for drone manufacturers to offer integrated lidar payloads (e.g. DJI with the L1); alternately, they may partner with a lidar system integrator to offer an out-of-the-box lidar mapping solution. Most payload designs from system integrators offer an industry standard mounting option, such as a gimbal or on-rail configuration, so payload and drone platform can be chosen independently of each other.

Due to the competitive market and the overall dynamic technology in the core subsystems (compact lidar system performance continues to improve significantly every 12-18 months), it is difficult to provide accurate and up-to-date price guidance for mapping professionals considering a system acquisition. Table I.D.1 below provides general price ranges for the various categories of systems on the market as of March 2023. This pricing includes the payload hardware, accessories, and post-processing software. It does not include the UAS or the aircraft itself. Due diligence in making price comparisons and obtaining competitive quotes on comparable systems is always recommended.

Table I.D.2 Market Value of Lidar System Cost as of March 2023

Group	Price Range (USD) (Full bundle based on March 2023 prices)	Notes
0 (Consumer)	$100s–$2,000	Not currently suitable for professional mapping applications. The lidar in a commercial phone or vacuum cleaner.

1a (< 2.5 kg)	\$10,000–\$20,000	Entry-level designs based on lowest-cost lidar and low-cost IMUs.
1b (< 2.5 kg)	\$30,000–\$100,000	Mid-range performance designs based on multichannel laser scanners, typically operating at 900 nm.
2a (< 10.0 kg)	\$100,000–\$150,000	Mid-range performance designs built with higher-performance 900 nm single-channel, purpose-built mapping lidars paired with higher-accuracy IMUs.
2b (<10.0 kg)	\$150,000–\$300,000	Highest-performance UAS designs that can also be used in low-altitude fixed-wing or helicopter configurations. Typically operating at 1.0–1.5 microns with single/dual channel designs.
3	\$500,000–\$1,500,000+	Highest-performance lidar systems with the greatest range and best accuracy available on the market. Purpose-built for large-area fixed-wing or helicopter operations. Includes high-performance bathymetric lidar systems.
4 (SLAM)	\$20,000–\$120,000	Range of system designs and mounting options for indoor (GNSS-denied) mapping applications. Hand-held, backpack, cart, and UAS mounts all available.

ADDENDUM II: BEST PRACTICES AND GUIDELINES FOR FIELD SURVEYING OF GROUND CONTROL AND CHECKPOINTS

CONTENTS

FIGURES:

TABLES:

PURPOSE

The purpose of this addendum is to provide best practices for the field surveying of ground control and checkpoints, as referred to throughout the ASPRS Positional Accuracy Standards for Geospatial Data. These guidelines are intentionally sensor and manufacturer agnostic. These best practices are not intended to replace the manufacturer's manual, nor do they replace surveying textbooks. Best practices recommended herein assume that the equipment operator and data processor understand surveying fundamentals and can competently operate the relevant equipment and software. These guidelines are not intended to instruct beginners in the performance of surveying tasks; rather, they represent a consensus reached by experienced professionals, and are intended to provide recommendations for seasoned surveyors.

SCOPE

Five methodologies for field surveying of ground control and checkpoints are covered in this Addendum:

1. Establishment of static control and best practices for utilizing Global Navigation Satellite System (GNSS) for Real-Time Kinematic (RTK) surveying using base and rover methodologies.
2. Use of GNSS Real-Time Networks (RTN).
3. Use of GNSS Real-Time Precise Point Positioning (RT-PPP) techniques to establish ground control in clear open-sky areas only.
4. Use of conventional surveying techniques (total station) to establish Vegetated Vertical Accuracy (VVA) checkpoints under tree canopy, incorporating RTK/RTN techniques for local control.
5. Use of terrestrial scanning and mobile mapping methodologies to establish ground control points (GCPs) and Non-Vegetated Vertical Accuracy (NVA) checkpoints under controlled circumstances.

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CAUTION

The surveying products described in this Addendum should only be provided by a competent and knowledgeable land surveyor who is familiar with the associated equipment, technology, and software. To ensure that survey projects meet the ASPRS Positional Accuracy Standards, it is absolutely necessary that the surveyor possess an appropriate understanding of error theory, practical surveying methodologies, and modern survey technologies such as survey-grade GNSS, geodesy, and map projections.

Additionally, it is recommended that the survey work described herein be supervised and certified by a professional land surveyor licensed in any one of the United States, as these professionals possess the requisite skill set to oversee survey projects and verify the accuracy of control points and collected data.

SECTION A: COORDINATE QUALITY OF CONTROL POINTS AND CHECKPOINTS

These guidelines are intended to assist field surveyors and Quality Assurance/Quality Control (QC) personnel in the determination of the reliability of field measurements intended to control for another type of geospatial data (e.g. aerial).

Because coordinate quality is collected in different ways and represented by different statistical means depending on the manufacturer, the professional surveyor must understand the coordinate quality definition particular to the software being used. According ASPRS specifications, each control point and checkpoint collected in the field should have a horizontal and vertical accuracy of two times better than that of the aerial or other geospatial data being controlled and verified. Therefore, the professional surveyor should ensure that his/her equipment, software, and field survey practices will allow the collected data to meet these requirements. It is always the professional surveyor's responsibility to ensure this is performed correctly.

To reliably estimate the quality of the positions of these surveyed points**,** multiple independent observations of each surveyed point must be made. Additionally, coordinate quality indicators must be provided in a standardized format. One value should be provided for each dimension, and one-sigma standard deviations, RMSE, CQ, or another appropriate statistical term should be included with all coordinate data. This information must be provided in any coordinate listing and/or survey report, as in the examples listed in Table II.A.1:

Table II.A.1 Survey Coordinate Samples

Point ID	Northing	Easting	Ortho Height	Horizontal RMSE	Vertical RMSE
G0001	496353.356	5941936.542	832.743	0.009	0.012

Point ID	Northing	Easting	Ortho Height	Hz Precision CQ 2D	Vert Precision CQ 1D
G0137	396353.356	3941936.542	1832.743	0.004	0.002

Point ID	Northing	Easting	Ortho Height	SD Northing	SD Easting	SD Ortho Height
N0108	460624.421	2641766.062	1083.664	0.01	0.01	0.00

The units of measure used must be indicated in the report or in the table.

SECTION B: STATIC CONTROL AND RTK SURVEYING

The purpose of this section is to set forth best practices and guidelines for the establishment of GNSS static control points and the use of GNSS RTK using base and rover methodologies. Furthermore, these guidelines will provide practical suggestions for obtaining consistent and accurate three-dimensional survey control.

B.1 Static Surveying with GNSS

Static surveying requires that two or more GNSS receivers occupy stations at the ends of baselines for a time period determined according to baseline lengths, satellite constellations, the potential for satellite signal interference, multipath, and/or blockage caused by trees, buildings, etc. Most manufacturers quote the recommended observation times and accuracy specifications based on ideal conditions, but survey points are frequently located in less-than-ideal GNSS environments. It is always advisable to err on the side of caution by extending the duration of occupations, to avoid having to go back and resurvey due to poor data.

While it is possible to use only two receivers for a static survey, multiple receivers configured in a network using multiple known and unknown points will give better results. At least one receiver must occupy a point with precise, known coordinates; other receivers may be set up at unknown points. Raw data should be collected at all receivers simultaneously for a predetermined amount of time, which, after post-processing of the baselines, will produce the coordinates of the unknown points.

This method of survey is most often used to perform precise positioning over large areas where baseline lengths are greater than real-time observations allow. The accuracy of the post-processed positions will be affected by the length of the various baselines, the observation duration of the survey, the precision of the equipment mounting system used, the number of independent redundant observations, and the accuracy of the existing control points used to constrain the survey.

B.1.1 Equipment

Numerous makes, models, and combinations of GNSS antennas, GNSS receivers, and data controllers are available on the current market and are continuously evolving. Usually, it is easiest to conduct surveys with antennas, receivers, and mounting equipment (tripods, tribrachs, and height measuring devices) from the same equipment manufacturer. However, surveyors should make equipment choices based on best practices, desired accuracy results, and project requirements. Be mindful that processing software and workflows can be manufacturer dependent.

B.1.2 Data Management

When planning static surveys, be mindful of data size and storage requirements, as well as pre-project observation planning. Consider the following when planning static surveys:

File Size & Storage Capacity: Consider the size and duration of your files and where the data will be logged. This is not usually a concern with modern GNSS receivers, but can become an issue with some older models. There must be enough free memory storage in the receiver for the desired survey. Modern receivers possess much larger storage capacities than their predecessors.

Data Sample Rate: For static surveys, it is common to collect data at a 5- to 15-second sampling interval, rather than at a 1-second interval. Data should be collected at the same interval for all receivers where possible—some Continuously Operating Reference Stations (CORS) will collect and disseminate data at a minimum of a 30-second rate, as shown in Figure II.B.1. Sample rate will directly affect the file size.

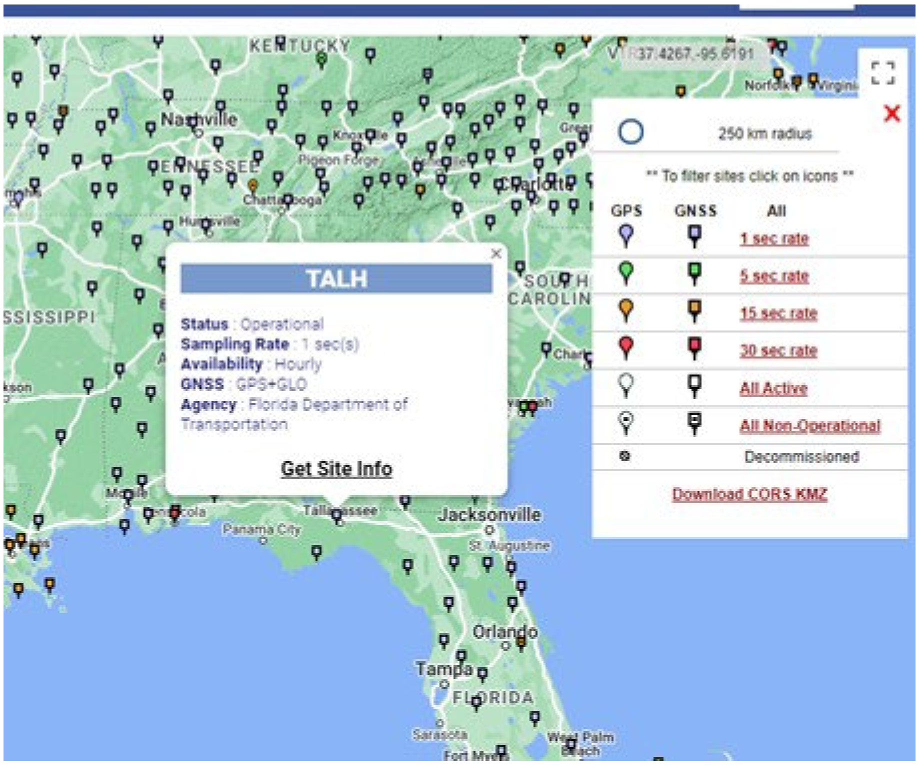

Figure II.B.1 CORS Station Data Sample Intervals (credit: NOAA NGS)

Elevation Mask/Cutoff Angle: Consider the environment and obstructions that may potentially block GNSS signals. Above what elevation mask do you want the receiver to log raw data? The commonly recommended value is 15 degrees. Remember that a low elevation mask will allow the collection of poorer-quality raw data due to signal blockage, multipath, atmospheric interference, etc. The use of a higher elevation mask will eliminate much of the poorer data, and will almost always improve the vertical component of the solution. The most advanced processing software can mitigate most of the effects of low-quality raw data, but not everyone uses the same software. Therefore, it is better to err on the side of caution rather than to have to go back and re-observe due to poor-quality raw data.

B.1.3 Workflow

Initial site analysis and pre-project planning are essential to project success, therefore it is essential to plan missions, pre-determine locations that possess adequate sky coverage, and minimize potential multi-path contributors. Always consider the environment being surveyed, and account for potential obstacles such as vegetation, structures, canyon walls, or any other objects that may obstruct your receiver's view of the satellites.

B.1.4 Preparation

- Plan for power needs. Bring adequate chargers and batteries.
- Plan for memory needs based on observation duration.
- Perform field reconnaissance in advance, utilizing whatever mapping resources you may have access to, including:

    - Topographic maps
    - Google Earth Pro®
    - Software-specific aerial imagery
- Pre-plan GNSS sessions. Anticipate the number of sessions and observers. Ensure observation times are adequate.
- Prepare a project mission plan with equipment checklists and GNSS planning schedules.
- Ensure good communication between the project teams while observations are ongoing.

B.1.5 Post-Processing

Post-Processing (interactive using commercially available software):

GNSS static data collected for high precision applications must be post-processed to produce accurate results. Specific workflows for post processing are software/manufacturer dependent; surveyors should consult the user manual for best results.

Post-Processing (Online Positioning):

Today there are several online positioning post-processing programs that can meet certain surveying needs. The requirements for each of these can be slightly different. The following are some of the most common options:

- OPUS (National Geodetic Survey). Users should always wait for the publication of the precise ephemeris for the most accurate results when utilizing the OPUS processing network.
- CSRS-PPP (Canadian Geodetic Survey)
- AusPos (Geoscience Australia)
- APPS (NASA/Jet Propulsion Laboratory)

B.2 Establishing Control Networks Using OPUS Projects

B.2.1 NOAA Technical Memorandum NOS NGS 92 (Currently Under Review)

It has come to our attention that the NGS will soon be releasing a new NOAA document relating to the creation of geodetic control surveys with GNSS, using the recently-released Version 5 of the OPUS Projects. This web tool is highly recommended by ASPRS, as it is able to make use of both static post-processing and RTK GNSS data when establishing survey control networks for least squares adjustment in order to yield coordinates and their estimated uncertainties for ground control points and checkpoints.

The title of this document will be “NOS NGS 92: Classifications, Standards, and Specifications for GNSS Geodetic Control Surveys using OPUS Projects,” and it will be available on the NGS website. The document states the surveying requirements necessary to meet certain classifications of accuracy when using OPUS Projects.

B.3 GNSS RTK Positioning

RTK surveying is a relative positioning practice that measures the three-dimensional vector between two or more GNSS receivers in real-time. One GNSS receiver (referred to as the base station) is set up at a known point with fixed coordinates. The base station transmits its known 3D position and the raw GNSS data it receives to the rover receiver in real-time, and the rover employs both the rover's and base station's GNSS data to compute its position relative to the base station.

RTK surveying requires a consistent and dependable communication link between the two receivers so that the rover receives continuous observation data from the base station. The communication method used from the base station to the rover can be by a UHF or VHF radio link, cellular network modems, or a combination of these two methods via an RTK bridge.

B.3.1 Base Station Setup

- A clear, unobstructed view of the sky above a 15-degree elevation mask is recommended.
- The base stations should be erected in stable environments.
- All setups should use properly adjusted, leveled, and maintained tripods and tribrachs. Tripod leg weights should be employed where necessary.
- Before sending crews to the field, it is preferable to upload the verified NAD83 geographic coordinates, as well as the ellipsoidal height for the monument to be used for the base station receiver, to the data collector/field controller. This is the most reliable way to set up the base station, as it prevents the field crew from having to choose a datum, a map projection, and a geoid model in which to work off, and it circumvents the need to key in coordinates manually. Entering incorrect base station data is the most common error associated with RTK surveying.
- Ensure that the antenna height is properly measured, checked, and verified by independent means. Fixed-height tripods or manufacturer-specific, survey-grade height hooks, which both provide vertical height measurements to the millimeter level, are preferable.

Please refer to Section C.2 when obtaining data from a real-time reference network.

B.3.2 Rover Setup

When starting an RTK survey, it is imperative to ensure that the rover is configured to achieve the desired accuracy of the survey. The following are important fundamentals that must be confirmed for quality data collection:

- Constellations tracked should be set in both the base and rover receivers to ensure that both are set up to track the same satellite constellations (GPS, GLONASS, GALILEO, BEIDOU) and signals (L1, L2, L5 and their equivalents).
- If required, a geoid model may be assigned. Heights observed by the GNNS receivers are ellipsoid heights. Geoid models are used to convert ellipsoidal heights to orthometric heights or elevations. At the present time, the most common geoid model used to convert ellipsoid heights to the NAVD88 datum in the US is Geoid18, although Geoid12B is still used occasionally. It is

anticipated that a new vertical datum based on a new 3D Coordinate Reference System (CRS) and a new gravity-based geoid model will be adopted by the National Geodetic Survey (NGS).

B.3.3 GNSS Solution Types

- *Autonomous*: When the rover is observing independently without any corrections and is not receiving data from the base. Coordinates gathered this way do not meet survey-grade accuracy standards.
- *Float*: When the data obtained at the rover is not of sufficient quality to calculate a fixed integer position—the most accurate and desirable type of position.
- *Fixed Integer*: When the GNSS rover can calculate a fixed integer solution, and the positional results are normally within the desired accuracy limits. This is the most accurate solution type.

Be mindful that not all survey grade GNSS systems employ the float/fixed method of RTK ambiguity resolution. This equipment variation may determine adequate RTK precisions based on a more rigorous float solution.

B.3.4 Rover Quality Control

- In the field, operators must ensure that all surveyed points meet minimum quality standards as set for the project. Revisiting points to re-survey checkpoints that do not meet minimum quality standards is not efficient, therefore it is important to ensure appropriate procedures and methodologies are followed before and during data collection. Delivering sub-standard survey data is not at all acceptable.
- Coordinate quality thresholds should be set to meet minimum project accuracy requirements.
- On older equipment, monitor PDOP and RMS values to ensure that quality solutions and measurements are obtained. Most modern GNSS equipment allows the user to set rigorous Coordinate Quality (CQ) standards, and therefore do not require the monitoring of PDOP or RMS values. Depending on the make and model of your equipment, many modern receivers do not display RMS, as it is a computed component of the precision calculations, and is handled through a threshold accuracy setting.
- A minimum of two independent measurements with independent initializations should be conducted on each checkpoint. More should be used if necessary. Subsequently, these independent measurements should be averaged or computed as a weighted mean to arrive at the best estimate of the checkpoint’s true position. It is crucial that, when doing so, any outliers are eliminated from the solution, as these may require additional independent observations in order to reach a reliable solution.
- It is recommended that a minimum observation period of 180 seconds be collected for each individual observation.

B.3.5 Accuracy Check

- It is always the obligation of the surveyor to use appropriate equipment and procedures to achieve and verify the required accuracy for the survey.

- RTK data collected in the field should always be checked and verified using the manufacturer's proprietary office processing software. Data collected in the field should never be exported directly to an ASCII file without an office QC process to catch any field errors and verify the correctness of the data before export.
- To verify that your base broadcast data and your Coordinate Reference System (CRS) are correct, you should locate and tie in existing NGS data or other monuments with known or published values using the same rigorous observation methodology as delineated above. Compare the coordinates published by NGS or other agencies to the surveyed coordinates as derived by your field crews to determine whether they fall within the standards required for the project.

Please refer to Section C2: Procedures and Best Practices for a more detailed explanation of some of these principles.

SECTION C: GNSS REAL-TIME NETWORKS (RTN)

The purpose of this section is to set forth best practices and guidelines for using a Real-Time Network (RTN) as the reference stations for ground control using RTK.

C.1 Introduction and Definitions

C.1.1 Network Solutions vs. Single Baseline Solutions

When predicting the coordinate quality values of a control survey, it is important to determine whether the reference being used is a single station (baseline), or a network solution.

The baseline length at which acceptable results can be achieved is sometimes shorter with a single baseline solution than with a network solution. A single baseline solution receives corrections from a single reference station, while a network solution models satellite orbit variations and ionospheric and tropospheric differences/interference using multiple reference stations in the area surrounding the rover, which helps the rover estimate the atmospheric conditions at its location. The distance of a single baseline solution can, however, be extended via cellular networks.

C.1.2 GPS vs. GNSS

When determining what type of accuracy and precision can be expected, it is critical to know not only which GNSS signals and constellations can be tracked by the rover, but also which signals and constellations can be tracked by the reference station/network. It does not matter how many constellations (GPS, GLONASS, GALILEO, BEIDOU) and signals (L1, L2, L5 and their equivalents) the rover is tracking if they are not also being tracked and utilized by the RTN. An RTK solution can only use satellites and signals that are being tracked at both the base and the rover.

C.1.3 VRS vs. MAC(X) vs. iMAX vs. FKP

There are significant differences in the type of RTN and how it affects the calculated rover position:

VRS – Virtual Reference Station: A virtual base station is created close to the rover's position and mitigates baseline dependent errors. The server sends modeled corrections to the rover, but the rover is unaware of the errors for which the VRS is modeling. As a result, there may be some degree of error in the virtual position that the rover is not accounting for, which can result in overly-optimistic quality predictions.

MAC(X) - Master Auxiliary Concept/Correction: Correction and modeling data from a primary (or master) station and auxiliary stations are broadcast to the rover, and the modeling is performed by the rover based on its position, information received from surrounding stations, baseline length to the closest physical station, etc. The master station is a physical reference station from which the rover receives corrections that can be traced and repeated.

iMAX – Individualized Master Auxiliary Correction: Based on the MAC(X) concept, but modified for lower bandwidth so that full GNSS, multi-signal messages can be transmitted successfully. Correction data is calculated at the server rather than the rover, but correction info and baseline vectors from the closest physical station are still transmitted to the rover. This allows the rover to predict coordinate quality based on the true baseline length.

FKP – Flachen-Korrektur Parameter: A model of distance-dependent errors is transmitted to the rover, and the calculations are performed at the rover. Because more data is transmitted to the rover than most network correction types, the bandwidth requirements are high. FKP is much more common in Europe and elsewhere than in North America.

C.1.4 Vertical and Horizontal Datums and Broadcast Coordinates

An understanding of reference frames, projections, geoid models, and their various realizations is critical when working with RTNs. The method and frequency of processing and adjusting the physical reference station coordinates can have a significant impact on the accuracy and precision possible at the rover, especially in areas of above-average horizontal or vertical movement.

C.1.5 Vertical and Horizontal Accuracy

The factors and variables at play in estimating and validating vertical and horizontal accuracy in an RTN are numerous, but with an understanding of the network type, rover capabilities, baseline length, best practices, etc. both high accuracy and high precision results can be obtained when using an RTN.

C.1.6 Baseline Length

Weather and ionospheric/tropospheric interference/differences are largely dependent on baseline length, which plays a huge role in the accuracy and precision of all RTK surveying. While network corrections are, to a certain extent, able to mitigate ionospheric and tropospheric differences through modeling, better coordinate qualities can be expected if the atmosphere through which GNSS signals are being received is similar at both the base and the rover. This is particularly true of the vertical component, due to the difficulty in estimating the tropospheric changes over long distances.

C.1.7 Dilution of Precision (DOP), Root Mean Square Error (RMS), and Coordinate Quality (CQ)

The same factors that affect accuracy and precision in traditional base-and-rover RTK surveying affect RTN surveying, but more variables are introduced into the solution for RTN. Technical considerations such as satellite constellations and signals tracked, satellite geometry, and dilution of precision become more complicated when handling baseline lengths in excess of twelve miles.

C.2 Procedures and Best Practices

C.2.1 Coordinate Quality/Root Mean Square Dilution of Precision Guidelines

To keep coordinate quality (CQ) and Root Mean Square (RMS) error values at an acceptable level, factors such as baseline length (especially in network RTK when baselines are not limited by radio range) and Dilution of Precision (DOP) values should be monitored and taken into account. Reliable results are possible at longer baseline lengths when the corrections are coming from a network cluster and modeled for ionospheric and tropospheric differences, as opposed to a single baseline solution in which baseline length has a direct impact on coordinate quality (roughly 1-2cm plus one part per million with most survey-grade GNSS receivers).

C.2.2 Satellite Constellation

Full GNSS tracking of constellations (GPS, GLONASS, GALILEO, BEIDOU) and signals (L1, L2, L5 and their equivalents) on both the network and the rover side will improve results on longer baselines in comparison to GPS or GPS and GLONASS only, as most modern GNSS receivers are able to automatically remove noisy or redundant signals from the solution. The more signals to choose from, the more lower-grade signals the solution can reject while still maintaining a sufficient number to fix integer ambiguities.

C.2.3 Baseline Length

Depending on the network type and signals being used, longer baselines can allow reliable results with proper procedures due to the ionospheric and tropospheric modeling inherent to network RTK corrections. While the network type (VRS, MAC(X), iMAX) has an effect on the achievable accuracy at the rover, any network correction type will greatly improve rover accuracy when dealing with longer baselines, due to the modeling that is not possible in a single baseline solution**.**

CAUTION: Be aware that VRS networks can display overly-optimistic CQ and RMS values due to the proximity of the rover to the virtual station, as opposed to the true baseline length to a physical station.

C.2.4 Occupation Time

Minimum occupation times of 180 seconds are recommended. This gives the rover enough time to improve the solution slightly, and allows some modern units time for secondary measurement engine calculations and checks to be completed, improving confidence in the solution. Please note that seconds are used here rather than epochs, due to the fact that many manufacturers allow epoch rates of less than 1 second (e.g. 20Hz, in which case a 180-epoch observation would only be 9 seconds long).

C.2.5 Redundant Occupation

A minimum of two (preferably three or more) occupations should be taken at each checkpoint. It is strongly recommended that the unit be re-initialized in a different location, at least 15 feet different horizontally and at least two feet different vertically, between observations to ensure any bad initializations are identified. It is statistically very difficult for two independent initializations, when initialized in different locations, to come up with bad initializations that agree with one another. If, on the other hand, no re-initialization is completed, or if a re-initialization is completed in the same location, the chances of bad solutions that are in agreement increase drastically.

In general, more occupations of a shorter duration (as long as the system is properly re-initialized between each observation) are preferrable to fewer observations of a longer duration, due to the accuracy advantages of identifying bad initializations, as well as the benefits of point averaging that are possible with multiple observations. However, it should also be recognized that there are two benefits to longer observation times: they may allow the real-time GNSS software to more easily identify and eliminate bad initializations, and they will usually produce slightly better results, as each epoch can be considered a measurement.

C.2.6 Point Averaging

Averaging multiple observations is a critical component of control surveying. Multiple observations from separate RTK initializations and, preferably, under different satellite constellations (e.g., different times of day) allow for the creation of a mean—ideally, a weighted mean based on coordinate quality values. This can not only help identify outliers or bad initializations, but may also result in an averaged value closer to the true coordinate than individual measurements are likely to be.

C.2.7 QA/QC

Best practices dictate that all field data is analyzed in the office utilizing QA/QC software—preferably the proprietary software of the hardware manufacturer—to ensure field data was collected properly. A competent office staff member who understands the QC process and is very familiar with the software being used must independently confirm that measurements were based on initialized or fixed integer solutions, with acceptable CQ and/or RMS error values, individual point averages to include (or exclude) the appropriate measurements per best practices, and other QA/QC routines. It is an extremely dangerous practice to accept and use a file exported directly from a data collector/field controller without any true QA/QC of the raw data and metadata via the appropriate office software.

SECTION D: GNSS REAL-TIME PRECISE POINT POSITIONING (RT-PPP) IN OPEN SKY AREAS

This section explains the fundamentals of and demonstrates best practices for using Real-Time Precise Point Positioning (RT-PPP) methodologies to establish control networks for remote sensing applications.

The following guidelines provide a practical method to obtain consistent, three-dimensional positions using a single rover. This is accomplished with real-time signal augmentation corrections designed to remove system errors due to satellite, atmospheric, and receiver-related influences through an inbound data feed.

D.1 Real-Time Precise Point Positioning (RT-PPP)

Real-Time Precise Point Positioning (PPP or RT-PPP) is an alternative to base-and-rover RTK, RTN-based Post Processed Kinematic (PPK), and static surveys, and it utilizes a hybridization of these methodologies. PPP relies on access to precise satellite orbit and clock products received through a data stream from either the satellites themselves or through an internet-based subscription. This data stream removes the need for a base station or a two-way connection to a real-time network to alleviate the broadcast and system positioning errors associated with a single roving receiver configuration. One benefit to utilizing a standalone receiver is the removal of the required tied baseline, thus resulting in a coordinate based on the satellite geometry instead of a conventional coordinate derivation relative to a base station as calculated in a RTN solution or similar RTK system.

D.1.1 PPP Convergence

Convergence relates to keeping positioning errors within a tolerable level, in order to create a final coordinate solution of acceptable quality. This will vary depending on the required accuracy of the control point.

The time the receiver takes to converge is known as the convergence time.

D.1.2 Rover Setup

- A clear, unobstructed view of the sky above a 15-degree elevation mask is preferred.
- Efforts should be taken to minimize the introduction of signal blockage and multipath errors generated from surfaces reflecting signal to the receiver (e.g., trees, buildings, etc.).
- All setups should be performed with adequately adjusted, leveled, and stable tripods and tribraches. Due to potentially long convergence and observation times (up to 15 minutes or more) a rod and bipod configuration may not provide sufficient stability and is not recommended.
- Ensure that the proper datum and projection are pre-selected, and that the antenna height is appropriately measured.
- PPP coordinates are computed in a globally-based reference frame, such as the International Terrestrial Reference Frame (ITRF), with the current epoch and transformed to a fixed epoch within the selected coordinate system of the user. This transformation may also introduce errors to the final coordinate solution due to inaccurate correlations between some coordinate systems. Changes to the desired datum and projection are not easily made after the fact. If a specific project-related coordinate system and datum are not specified, follow the National Spatial Reference System (NSRS) recommendation for the current coordinate system guidelines.

D.1.3 Rover Quality Control

- Observations can begin once convergence has been achieved.
- Coordinate auto-store accuracy thresholds should be lower than project accuracy requirements.
- Routinely re-measure previously measured points to ensure quality.
- A minimum of two (and preferably three) independent measurements which all meet the required project accuracy specifications, each with a different initialization, should be conducted on each point to ensure quality.
- It is recommended that a minimum observation time of 300 seconds or more should be collected for each observation. Due to the nature of how the RT-PPP solution is derived, it will require longer observation times to achieve acceptable results than with RTK or RTN solutions.

D.1.4 Accuracy Check

The surveyor must always use appropriate equipment and procedures to achieve the required accuracy for the survey.

To ensure that appropriate results are being achieved, locate, and observe existing NGS or other known geodetic monuments using the same rigorous observation methodology delineated above. Compare the coordinates published by NGS or other agencies to the surveyed coordinates as derived by your field crews to determine if they match the standards required for the project.

D.1.5 PPP Limitations

- Convergence times may vary greatly. They typically range from 1–20 minutes, depending on the performance of the correction services within the rover's region.
- The achievable accuracy for PPP may be variable, but generally falls in the range of 1–2 cm horizontal and 3–5 cm vertical under optimal conditions if rigorous quality control methodologies are followed and multiple observations are made.
- Current PPP broadcast correction services may only include certain constellations unless certain access fees are paid. The Real-Time Service (RTS), provided by the International GNSS Service (IGS), is offered as a GPS-only operational service.

SECTION E: CONVENTIONAL SURVEYING FOR VVA CHECKPOINTS UNDER TREE CANOPIES

The purpose of this section is to lay out the best practices and guidelines for utilizing a total station to measure Vegetated Vertical Accuracy (VVA) assessment points under tree canopy. This section is only meant to highlight these guidelines and is not a replacement for adequate education and experience in surveying practices.

A total station is a modern surveying instrument that measures horizontal and vertical angles, along with slope distances between the total station and an object (usually a prism on a range pole). Total stations have onboard microprocessors to assist with level compensation and allow for the station to calculate averages for multiple angle and distance measurements. Total stations are rated based upon their angular accuracy and distance measuring capabilities. Common total station angular accuracies include 1", 3", and 5", with 1" being the most accurate.

A total station may be combined with a data collector to allow for real-time conversion of the angular and distance measurements into X,Y,Z coordinates in the form of northings, eastings, and elevations. Some total stations may have onboard data collection software that can be accessed through a user interface, and more advanced total stations have robotic tracking capabilities (for potential single-person operation) and some limited scanning capabilities. It is important to note that total stations are precision instruments that require regular adjustment and calibration.

This section assumes that control points will be established for a total station with GNSS RTK or RTN methods. Please see Sections 1 and 2 for more information on real-time GNSS surveying techniques.

E.1 Temporary Control Points for Total Stations

A temporary control point is a semipermanent point with a known northing, easting, and elevation that can used as a total station occupation point, backsight point, or checkpoint. This section assumes that temporary control points will be measured in real time with GNSS methods. Please see Sections 1 and 2 for more detailed information on these technologies.

Temporary control points established using real-time GNSS techniques should be established in locations with clear views of the sky and limited multipath issues. The control points should be placed in relatively stable materials to ensure that the position of the control point does not change over the duration of the survey. A minimum of three temporary control points should be established for total station work, consisting of an occupation point for the total station, a backsight point, and a checkpoint to verify that horizontal and vertical errors are within acceptable limits. The occupation point should provide a good view into the area of interest where the VVA points are to be collected. The backsight point should be located as far away from the occupation point as is practical to minimize the angular errors in the data collection.

E.2 Total Station Data Collection Recommendations

The following is a list of recommended best practices for collecting data with a total station:

- Verify total station calibration.
- Follow a systematic data collection methodology to ensure adequate and accurate data is collected.
- Verify the height of the range pole and, if necessary, adjust before beginning the survey.
- Ensure that the range pole is plumb (in vertical adjustment).
- Use a bipod or tripod to set up the total station.
- Direct and reverse measurements should be taken and averaged when backsighting and collecting points (foresights).
- Utilize checkpoints.
- A hardened point should be used on bottom of the range pole for temporary control points and a “topo foot” should be used to collect VVA or other topographic points.
- If the height of the range pole is changed during data collection, ensure that the data collector or onboard software is updated to reflect the correct height.
- No data collection points should be farther away from the occupation point than the distance between the occupation point and the backsight point. This is especially important when establishing GCPs and NVA checkpoints.

E.3 Traversing into Vegetated Areas

When it is necessary to traverse into vegetated areas, the guidance above still applies. As the total station is a line-of-sight instrument, planning and forethought is required to set subsequent instrument occupation points. In addition to finding an occupation point that allows adequate visibility of the region of interest, the previous occupation point needs to be visible. It is also recommended that the checkpoint remains visible, or another checkpoint is set. When additional traversing is required, a traverse closure and adjustment routine should be used.

SECTION F: TERRESTRIAL SCANNING OR MOBILE MAPPING FOR GCPS AND NVA CHECKPOINTS

This section is intended to provide best practices and guidelines when utilizing existing point cloud data collected either by mobile mapping systems (MMS) or static terrestrial-based lidar for the purposes of controlling or verifying aerial lidar and photogrammetrically-derived products. The cost to acquire MMS or terrestrial-based lidar data for the sole purpose of establishing control points/checkpoints would be prohibitive, therefore, this section will focus on the re-use of existing ground-based point clouds to extract ground control points and/or checkpoints.

A mobile mapping system (MMS) is a vehicle-mounted array of sensors and a computer that can incorporate three-dimensional positioning with data collected from a variety of active and passive sensors. The most common sensors in MMS arrays are Inertial Navigation Systems (INS), which consist of integrated GNSS receivers and inertial measurement units, lidar, and cameras. As the vehicle moves, a constant stream of three-dimensional coordinates and sensor data are sent to the computer. This allows the computer to relate the position of the vehicle to the measurements taken from the sensors, and then compile one large point cloud that contains all of the measurements acquired.

Static terrestrial lidar is mounted on a tripod and positioned at various locations. The scans collected at each location are combined into one point cloud by registering the scans together. This is accomplished either by aligning common features that appear in multiple scans, or through registration of known coordinates based on the features visible in the individual scans.

F.1 Permitted Use

Determine if the point cloud was collected for another client, or if deliverables produced from that point cloud were contracted by another client. It is a good idea to seek permission from the client for whom the data was originally collected before use.

F.2 Selecting a Suitable Point Cloud

There are many factors that can affect the suitability of reusing previously-collected data. Care should be taken when selecting a suitable point cloud to use. Below are some areas that should be investigated to determine if the point cloud is suitable:

- What sensor was used for the ground-based collection? Do the ground-based sensor specifications meet/exceed the airborne project's specifications?
- Determine if the point cloud density meets/exceeds the current project specifications.
- Are photo-identifiable points easily recognizable?
- Is the point cloud density high enough that features are not hidden due to the point spacing?

- Was the point cloud constrained to survey control, or was it uncontrolled? If the former, what survey techniques were used to establish the control?
    - Static GNSS, RTK or RTN GNSS, Leveling, Total Station?
    - Were redundant measurements obtained?
- Review the point cloud registration statistics. These statistics should exceed the requirements for the airborne project.

F.3 Spatial Reference System

The CRS of the existing dataset will need to align with the aerial product's CRS, or else a transformation will need to be applied. To ensure the data aligns between the two projects, the horizontal datum, projection, adjustment date, epoch, vertical datum, and geoid model should be identified. If one of the products has been taken by ground coordinates, the combined factor and scaling origin also need to be determined in order to reverse the process.

F.4 Verifying the Point Cloud

Perform a site visit to see if any noticeable alterations have taken place since the point cloud collection:

- Have any of the roads been realigned?
- Does any of the pavement look different or newer?
- Is there evidence of earthwork or construction?
- Has any pavement restriping occurred?

F.5. Field Checking the Point Cloud

It is prudent to check ground-based lidar by surveying features in the point cloud. This can bring to light any discrepancies in the stated horizontal and vertical datum, as well as potential alterations to the site. Compare the derived position of the point cloud to the recently-surveyed position and determine if the error is within the project specifications.

F.6 Extracting Control from the Point Cloud

Once it has been verified that the point cloud represents the current conditions and is in the same CRS as the aerial project, the extraction process can begin.

When selecting points from a point cloud that was collected on the ground, be sure that the points selected have an unobstructed view of the sky. Think about tree canopy, building overhangs, and shadows that would prevent the point from being recognized in the aerial data.

For aerial products, it is a good idea to locate features that do not have a sudden elevation change nearby. Selecting a point at the edge of a roadway that has an adjacent ditch, at the top or bottom of a wall, or at a headwall are poor choices. Depending on the aerial lidar point spacing or shadows in the photography, these points may not be discernable in the aerial data.

- It is a good idea to make sure the point cloud has been cleaned of points that were measurements on transient objects, vehicles, or pedestrians present during the collection.

- When selecting points to extract, rotate the perspective to verify the location selected is the intended location. Often, different parts of the point cloud are selected unknowingly, but rotating the view will reveal if the correct position was selected.

CAUTION: While Terrestrial Scanning and/or MMS technologies may be useful when establishing ground control points and checkpoints, they must be employed carefully and only when all the above-noted checks and balances are in place. Indiscriminate use without some degree of ground verification by the surveyor can lead to disastrous consequences.

CERTIFICATION:

The following statement is an example of the certification which should accompany the delivery of the ground control points and checkpoints:

I, _____(FULL NAME) _____________do hereby certify that the ground control points and checkpoints provided herein meet the requirements as promulgated in the ASPRS Positional Accuracy Standards for Digital Geospatial Data Edition 2 Version 1.0.0, and this Addendum, and that the coordinate and Coordinate Quality values are true and correct to the best of my knowledge and belief .

____, ________________________

Signature & Professional Land Surveyor Designation , Date

ADDENDUM III: BEST PRACTICES AND GUIDELINES FOR MAPPING WITH PHOTOGRAMMETRY

TBD

ADDENDUM IV: BEST PRACTICES AND GUIDELINES FOR MAPPING WITH LIDAR

TBD

ADDENDUM V: BEST PRACTICES AND GUIDELINES FOR MAPPING WITH UAS

TBD