# ASPRS Positional Accuracy Standards for Digital Geospatial Data

**(EDITION 2, VERSION 1.0 - FEBRUARY 2023)**

## CONTENTS

# FOREWORD

The 1st Edition 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 the 1st Edition 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.
- Member: 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. The Standards are also designed to recommend best practices, methods, and guidelines for the use of emerging technologies and methods 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 Addendums 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 the 2nd Edition

Important changes adopted in this 2nd Edition are:

1. Elimination of 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 the 1st Edition of the ASPRS Positional Accuracy Standards for Digital Geospatial Data published in 2014. However, RMSE is also reported as it is the quantity computed from the error distribution from which accuracy at the 95% confidence level is derived. The reporting of two quantities representing the same accuracy at different confidence levels is problematic for users and data providers alike.

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

2. Relaxation of the accuracy requirement for ground control and checkpoints.

. R*eason for the change:* The 1st Edition 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 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 the 1st Edition exceed those that can be cost-effectively achieved even with high-accuracy GPS. Furthermore, today's sensors, software, and processing methods are more precise, and the errors introduced in data acquisition and processing are diminishing. If best practices are followed, safety factors of three and four times the intended product accuracy are no longer needed.

3. Consideration of survey checkpoint accuracy when computing final product accuracy

. *Reason for the change:* As stated in item 2 above, the margin between checkpoint error and final product error is decreasing. Relaxing the three times intended product accuracy requirement for checkpoints means that error in the checkpoints is approaching the same order of magnitude as the allowable error of the final product. 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, including the uncertainty associated with the checkpoints provides a better estimate of the reliability of these subsequent measurements.

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

. *Reason for the change*: Data providers 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 to make a pass/fail decision for the overall project. VVA should be evaluated and reported but should not be used as a criterion for acceptance.

. J*ustification 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, accuracy of the lidar-derived surface under trees is affected by 1) the density of lidar points reaching the ground and 2) the performance of algorithms used to separate ground and above ground points in these areas. Furthermore, the accuracy of the ground checkpoints acquired with GPS 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. Increase the minimum number of checkpoints required for product accuracy assessment from twenty (20) to thirty (30).

. *Reason for the change:* In the 1st Edition, a minimum of 20 checkpoints are required for testing positional accuracy of 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 Standard published by the U.S. Bureau of the Budget in 1947.

. *Justification for the change:* The Central Limit Theorem calls for at least thirty (30) samples to calculate statistics, such as mean, standard deviation, and skew that are relied upon in positional accuracy assessment. According to The Central Limit Theorem, regardless of the distribution of the population, if the sample size is sufficiently large (n ≥ 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. In the 2nd Edition, the Central Limit Theorem is used to justify the increase in the minimum number of checkpoints to thirty (30) for any product accuracy assessment to be considered fully compliant.

6. Introduction of a new term, “three-dimensional positional accuracy."

. *Reason for the change:* Three-dimensional models require consideration of three-dimensional accuracy rather than separate horizontal and vertical accuracy. The 2nd Edition 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; a method for assessing positional accuracy of a point or feature the 3D model is needed to support future innovation and product specifications.

7. Addition of Best Practices and Guidelines Addendums for:

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

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

## Foreword to the 1st Edition of 2014

The goal of American Society for Photogrammetry and Remote Sensing (ASPRS) is 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.

This standard was developed by the ASPRS Map Accuracy Standards Working Group, a joint committee under the Photogrammetric Applications Division, Primary Data Acquisition Division, and Lidar Division, which was formed for the purpose 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

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## 1. PURPOSE

The objective of the ASPRS Positional Accuracy Standards for Digital Geospatial Data is to replace the legacy ASPRS Accuracy Standards for Large-Scale Maps (1990), and the ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data (2004) to better address current technologies.

This standard includes 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 standard to address higher accuracies and higher spatial resolution achievable with newer technologies. The standard 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.

### 1.1 Scope and Applicability

This standard is intended to be broad based and technology independent, applicable to most common mapping applications and projects. Specifically, this standard is to be used by geospatial data providers and data users to specify the positional accuracy requirements for final geospatial products; it does not address classification accuracy for thematic maps.

The 2nd edition of this standard provides best practices and guidelines recommended to meet 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 provider 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

The 2nd edition of this standard addresses accuracy thresholds and testing methodologies achievable with current technology. It also addresses shortcomings in the 1st Edition pointed out by users of the standards over the decade following its publication.

Additional accuracy assessment needs identified by the Working Group but not addressed in the 2nd edition 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 distribution and density.
- alternatives to TIN interpolation for vertical accuracy assessment.

Just as the 2nd edition addresses technology advancements of the last decade, it is intended that future advancements can be addressed in future editions. As stated in the Foreword, the 2nd edition includes four addendums on best practices and guidelines for photogrammetry, lidar, UAS, and field surveying. Additional addendums should be developed by subject matter experts and submitted to ASPRS for review and publication.

To date, this standard does 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 standard (Sections 1 through 7), according to the ASPRS standards template and without extensive explanation or justification.

Detailed supporting background information and accuracy conversion examples are given in Annexes A through D.

- Annex A provides a background summary of other standards, specifications and/or guidelines relevant to ASPRS but which do not satisfy current requirements for digital geospatial data.
- Annex B provides accuracy/quality examples and overall guidelines for implementing the standard.
- Annex C provides guidelines for accuracy testing and reporting.
- Annex D provides examples on computing vertical accuracy in vegetated and non-vegetated terrain.

Addendums I through IV present best practices and guidelines in the following areas of practice:

- Addendum I: Best Practices and Guidelines for Mapping with Photogrammetry
- Addendum II: Best Practices and Guidelines for Mapping with Lidar
- Addendum III: Best Practices and Guidelines for Mapping with UAS
- Addendum IV: Best Practices and Guidelines for Field Surveying for Positional Accuracy Assessment

## 2. CONFORMANCE

No conformance requirements are established for this standard.

## 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*.

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

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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 Annex A.

## 4. AUTHORITY

The responsible organization for preparing, maintaining, and coordinating work on this standard 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 the 2nd edition. 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 datum.
- *accuracy* – The closeness of an estimated value (for example, measured or computed) to a standard or accepted (true) value of a particular quantity. Not to be confused with *precision*.
- *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. Blunder is not an error, and it should be avoided.
- *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 equal to or smaller 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.
- *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)* – The primary component of an IMU. Measures 3 components of acceleration and 3 components of rotation using orthogonal triads of accelerometers and gyros.
- *inertial navigation system (INS)* – A self-contained navigation system, comprising several subsystems: IMU, navigation computer, power supply, interface, etc. Uses measured accelerations and rotations to estimate velocity, position, and orientation. An unaided INS loses accuracy over time, due to gyroscopic drift.
- *kurtosis* –The measure of relative "peakedness" or "flatness" of a distribution compared with a normally-distributed data set. Positive kurtosis indicates a relatively peaked distribution near the mean, while negative kurtosis indicates a flat distribution near the mean.
- *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.
- *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, as it is the magnitude of the errors, 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, strictly speaking, 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, and, therefore the values referred to as "errors" throughout these standards should more formally be referred to as "residuals."
- *precision* – The closeness with which measurements agree with each other, even though they may all contain a systematic bias.
- *resolution* –The degree of fineness to which a measurement can be made. 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, 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, processing or 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. It can also be defined as 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 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 Users 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
- IFSAR - Interferometric Synthetic Aperture Radar
- IMU - Inertial Measurement Unit
- INS - Inertial Navigation System
- NGPS - Nominal Ground Point Spacing
- NPD - Nominal Pulse Density
- NMAS - National Map Accuracy Standard
- 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 (also referred to as $RMSE_Z$)
  - $RMSE_X$ - 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). Also referred to as $RMSE_V$
- TIN - Triangulated Irregular Network
- VVA - Vegetated Vertical Accuracy
- $\overline{x}$ - sample mean error
- $\sigma$ - sample standard deviation
- $\gamma 1$ - sample skewness
- $\gamma 2$ - sample kurtosis

# 7. SPECIFIC REQUIREMENTS

This standard defines 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 and ground control network used for the data set and as specified in the metadata. Ground control accuracies and survey procedures should be established based on 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). When local control is needed to meet specific accuracies or project needs, it must be clearly identified both in the project specifications and the metadata.

## 7.1 Statistical Assessment of Accuracy

Horizontal accuracy is to be expressed as $RMSE_{H}$, derived from two horizontal error components, $RMSE_{X}$ and $RMSE_{Y}$, as described in Section 7.3. Vertical accuracy is to be expressed as $RMSE_{V}$, as described in Section 7.4. Three-dimensional positional accuracy is to be expressed as $RMSE_{3D}$ derived from horizontal and vertical accuracy component, $RMSE_{H}$ and $RMSE_{V}$, as described in Section 7.5. Furthermore, elevation data sets shall also be assessed for horizontal accuracy ($RMSE_{H}$) whenever possible, as outlined in Section 7.6.

More details on application and calculation of these statistics are found in in Annex 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 this standard 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 provider to test and verify that the data meet this requirement by evaluating all statistical parameters, including standard deviation, median, mean, and RMSE as they may help in discovering and diagnosing 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 provider 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 be reported in the metadata. If further action is taken to correct bias to reduce the mean error, this action should also be reported in the metadata. Finally, if the data provider and client agree to accept a mean error greater than 25% of the RMSE, this should also be reported in the metadata.

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 this standard. 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. This standard specifies 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, this standard allows more flexibility; it does not classify horizontal accuracy discretely nor does it tie accuracy class to map scale.

According to this standard, 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 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.

**Table 7.1 Horizontal Accuracy Classes for Geospatial Data**

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

Annex B includes examples that relate accuracy classes as defined in this standard to equivalent classes in legacy standards. Table B.5 provides $RMSE_H$ recommendations for digital orthoimagery of various pixel sizes. Table B.6 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 the above-mentioned tables of Annex B 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. This standard does 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 non-vegetated terrain and vegetated terrain. Vertical Accuracy Classes are defined by the associated $RMSE_V$ specified for the product. 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 provider 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) |
| *X-cm* | *≤ X* | *As found* | *≤ 0.60*X* | *≤ 0.80*X* | *≤ 1.60*X* |

Table B.7 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.8 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 $RMSE_V$ computed relative to checkpoints, even when the surface lacks sufficient resolution to represent details present in the terrain. Table B.9 therefore 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, rocks, 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 needs only to be tested according to the requirements set forth in this standard and reported in metadata.

## 7.5 Three-Dimensional Positional Accuracy Standard for Geospatial Data

Table 7.1 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 horizontal and vertical component of error according to the following formula:

$$RMSE_{3D} = \sqrt{RMSE_x{}^2 + RMSE_y{}^2 + RMSE_z{}^2}$$

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) |
| *X*-cm | *≤ X* |

## 7.6 Horizontal Accuracy of Elevation Data

This standard specifies horizontal accuracy for elevation data created from stereo photogrammetry and lidar. For other technologies, appropriate horizontal accuracies for elevation data should be negotiated between the data provider and the client, with specific accuracy thresholds and methods derived based on the technology used and the project design. In these cases, the data provider 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, assuming positional accuracy of the GNSS; roll, pitch, and heading accuracy of the Inertial Measurement Unit (IMU); and the flying height are quantified:

$$Lidar\ Horizontal\ Error(RMSE_H) = \sqrt{(GNSS\ positional\ error)^2 + \left(\frac{\tan\,(IMU\ role\ or\ pitch\ error) +\ \tan\,(IMU\ heading\ \ error)}{1.47800114} *\ flying\ height\right)^2}$$

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,
- 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.

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[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.

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

$$FH = \frac{1.47800114}{tan(IMU\ roll\ or\ pitch\ error) +\ tan(IMU\ heading\ error)} \sqrt{{RMSE_H}^2 - (GNSS\ positional\ error)^2}$$

Table B.10 expresses estimates of horizontal error ($RMSE_H$) as a function of flying height using on 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; it occurs with lidar or radar where there is poor penetration of signal. This standard requires that such low confidence areas be delineated by polygons and reported in the metadata. Low confidence polygons are the digital equivalent of dashed contours referred to in legacy standards.

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 IMU-based sensor orientations (if used for 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 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 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 $RMSE_Z$ can be relaxed. For this reason, the standard recognizes two different criteria for aerial triangulation accuracy:

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

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 $RMSE_{V(AT)}$ less than or equal to target $RMSE_H$ for the final product requires a stringent workflow to control camera deformation 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):
    - $RMSE_{H(AT)} \leq ½ * RMSE_{H(Map)}$
    - $RMSE_{V(AT)} \leq ½ * RMSE_{V(DEM)}$

Scrutinizing the results of aerial triangulation is a strongly recommended quality assurance step in the creation of any photogrammetric product. In the case where 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 product. If the final products meet target accuracies, an agreement to accept the aerial triangulation results should be made between the data provider and client and reported in the project metadata.

Section B.1 provides examples of the practical application 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:
    - $RMSE_{H(GCP)} \leq ½ * RMSE_{H(MAP)}$
    - $RMSE_{V(GCP))} \leq RMSE_{H(MAP)}$
- Ground control for aerial triangulation designed for projects that include elevation or 3D products, in addition to digital planimetric data (orthoimagery and/or map):
    - $RMSE_{H(GCP)} \leq ½ * RMSE_{H(MAP)}$
    - $RMSE_{V(GCP)} \leq ½ * RMSE_{V(DEM)}$

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.

- $RMSE_{V(GCP)} \leq ½ * RMSE_{V(DEM)}$

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, having 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.

### *7.11.1 First Component of Positional Error – Product Fit to Checkpoints*

The surveyed coordinates of every checkpoint should be compared to the coordinates of that checkpoint as derived from the tested product. Discrepancies between the two sets of coordinates for each checkpoint should be computed and tabulated. The first component of error, RMSE, represents the product fit to checkpoints. RMSE should be computed in each dimension from all the individual computed discrepancies 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:

$$RMSE_{H1} = \sqrt{{RMSE_X}^2 + {RMSE_Y}^2}$$

The first component of vertical error is:

$$RMSE_{V1} = RMSE_Z$$

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

The second component of positional error that needs to be considered is the error of the survey control and checkpoints[2]. These errors cannot be considered negligible, particularly when the requirement for survey point accuracy has been relaxed in this standard to two times the target product accuracy.

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

The second component of horizontal error is represented as $RMSE_{H2}$, and is the quantity reported by the field surveyor.

The second component of vertical error is represented as $RMSE_{V2}$, and is the quantity reported by the field surveyor.

### *7.11.3 Horizontal Product 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 $RMSE_{X2} = RMSE_{Y2}$

Using error propagation principles for Euclidean vectors:

$$Horizontal\ Product\ Accuracy = \sqrt{{RMSE_{H1}}^2 + {RMSE_{H2}}^2}$$

### *7.11.4 Vertical Product Accuracy*

Vertical product accuracy is computed from the 1st and 2nd components of vertical error:

$$Vertical\ Product\ Accuracy = \sqrt{{RMSE_{V1}}^2 + {RMSE_{V2}}^2}$$

Table 7.4 provides examples of vertical product accuracy assuming that the vertical survey point error reported by the surveyor is $RMSE_{V2}$ = 2.0 cm. Additional details can be found in Section C.6.

**Table 7.4 Computing Vertical Product Accuracy**

| Fit to Checkpoints $RMSE_{V1}$ (cm) | Survey Checkpoint Accuracy $RMSE_{V2}$ (cm) | Vertical Product Accuracy $RMSE_V$ (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 this 2nd edition of the standard, 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.

Horizontal checkpoints shall be established at well-defined points. A well-defined point is a feature for which the horizontal position can be placed with a high degree of certainty in the product being tested and measured to the required degree of accuracy with respect to the geodetic datum. Well-defined points must be easily visible or identifiable on the ground or on the independent source of higher accuracy, and on the product itself. In the case of orthorectified imagery, well-defined points shall not be selected on features that are above the elevation surface to rectify the imagery. 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; if the imagery was orthorectified using 3D model that includes buildings, then a point on the building rooftop may be an acceptable horizontal checkpoint.

Vertical checkpoints are not required to be well-defined points as defined above for horizontal checkpoints. Vertical checkpoints shall be established at locations that minimize interpolation errors when comparing the product elevation surface to the elevations of the checkpoints. Vertical checkpoints shall be surveyed in open terrain that is flat or in areas of uniform slope ≤ 10 percent (5.71 degrees). Vertical checkpoints should not be placed near vertical artifacts or abrupt changes in elevation.

## 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 between data provider and the client. In no case, shall the assessment of planimetric accuracy of digital orthoimagery be based on less than thirty (30) checkpoints. Similarly, the assessment of the NVA or VVA of elevation data should be based on no less than thirty (30) checkpoints each. If either horizontal or vertical accuracy is assessed using less than thirty (30) checkpoints, a special reporting statement should be used as outlined in section 7.15.1.2.

A quantitative methodology for characterization and specification of the spatial distribution of checkpoints, accounting 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.

Annex C provides detailed guidelines and recommendations for checkpoint density and distribution. The requirements in Annex 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 reveal potential systematic errors, such as are related to sensor stability, quality of GNSS trajectories, ranging precision, calibration of sensor models, and boresight alignment. Assessment of data internal precision includes two aspects of data quality: within-swath (smooth-surface) precision and swath-to-swath precision. As previously 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 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 differenced. 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 swath, following guidelines set forth in Section C.11. An elevation is extracted from each surface at a number of point sample locations and an elevation difference 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 reported in terms of accuracy classes as set forth in this standard.

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

- 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*

The positional accuracy of digital orthoimagery, planimetric data, and elevation data products shall be reported in the metadata in one of the following manners:

- 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, 2nd Edition (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, 2nd Edition (2023) for a __(cm) $RMSE_Z$ Vertical Accuracy Class. NVA accuracy was found to be $RMSE_Z$ = __(cm)." VVA accuracy was found to be $RMSE_Z$ = __(cm)."*

  - Reporting Three-Dimensional Positional Accuracy

    *"This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data, 2nd Edition (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, 2nd Edition (2023). Although the standard calls 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, 2nd Edition (2023). Although the standard calls for a minimum of thirty (30) checkpoints, this test was performed using ONLY __ checkpoints. This data set was produced to meet a ___(cm) $RMSE_Z$ horizontal positional accuracy class. The tested horizontal positional accuracy was found to be $RMSE_Z$ = ___(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, 2nd Edition (2023). Although the standard calls 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 Provider*

If rigorous testing is not performed, accuracy statements should specify that the data were "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 providers who employ mature and established technologies, following best practices and established procedures for project design, data processing and quality control, as are set forth in the Addendums to this standard.

If the data provider has demonstrated that they are able to produce repeatable, reliable results, and they are thereby 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, 2nd Edition (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, 2nd Edition (2023) for a __(cm) $RMSE_Z$ Vertical Accuracy Class.*

- Reporting Three-Dimensional Positional Accuracy

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

# ANNEX A — BACKGROUND AND JUSTIFICATIONS (INFORMATIVE)

## A.1 Legacy Standards and Guidelines

Accuracy standards for geospatial data have broad applications nationally and/or internationally, whereas specifications provide technical requirements/acceptance criteria that a geospatial product must conform to in order to be considered acceptable for a specific intended use. Guidelines provide recommendations for acquiring, processing and/or analyzing geospatial data, normally intended to promote consistency and industry best practices.

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 Standard* (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 while not changing 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 from 1990 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.” In its Appendix 3-A, the NSSDA provides equations for converting RMSE values in X, Y, and Z into horizontal and vertical accuracies at the 95% confidence levels. The NSSDA assumes normal error distributions with systematic errors eliminated as best 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, based on the NSSDA's $RMSE_Z$ * 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 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. The NDEP Guidelines, while establishing alternative procedures for testing and reporting the vertical accuracy of elevation data sets when errors are not normally distributed, also 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, to include FVA, SVA and CVA reporting. Similarly, the ASPRS 2004 Guidelines, while endorsing the NDEP Guidelines when elevation errors are not normally distributed, also 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 $RMSE_z$ thresholds and 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). With 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' 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 accuracy standards that are universally applicable.

- In 2012, USGS published its Lidar Base Specification, Version 1.0, which is based on $RMSE_z$ 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; each Quality Level having different $RMSE_z$ 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 in which IFSAR Quality Level 5 data are specified with $RMSE_z$ between 1 and 2 meters and with 5 meter post spacing. The 3DEP lidar data are expected to be high resolution data 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, respectively replacing the older elevation data from the USGS' National Elevation Data set.

- In 2014, the latest USGS Lidar Base Specification Version 1.2 was published to accommodate lidar Quality Levels 0, 1, 2 and 3.
- In this version of the standard, the accuracy measure of 95% confidence level is removed due to the confusion it creates for users of the standard. Providing two accuracy measures in one standard proved to be problematic for users. However, when 95% confidence interval reporting is required, readers are referred to Section B.7 and Addendum B.

## A.2 New Standard for a New Era

The current standard was developed in response to the pressing need of the GIS and mapping community for a new standard that embraces the digital nature of current geospatial technologies. The following are some of the justifications for the development of the new standard:

- Legacy map accuracy standards, such as the ASPRS 1990 standard 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 medium 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. New mapping processes and methodologies have become much more sophisticated with advances in technology and advances in our knowledge of mapping processes and mathematical modeling. 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, quality and size of a Charged Coupled Device (CCD) used in the digital camera CCD array, amount of imagery overlap, quality of parallax determination or photo measurements, quality of the GPS signal, quality and density of ground control, quality of the aerial triangulation solution, 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 current geospatial mapping practices.

- Elevation products from the new technologies and active sensors such as lidar and IFSAR are not considered by the 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*

Since the early history of photogrammetric mapping, film was the only medium to record 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. A film-to-map enlargement ratio value of 6 and a c-factor value of 1800 to 2000 were widely accepted and used during this early stage of photogrammetric mapping. C-factor is used to determine the flying height based on the desired contour interval from 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 the 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 providers 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 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, rigid body construction, and precise electronics. These new camera technologies, coupled with advances in the airborne GPS and mathematical modeling performed by current photogrammetric processing software, make it possible to extend the limits on the flying altitude and still achieve higher 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 guidelines like using a film-to-map enlargement ratio value of 6 and a c-factor between 1,800 to 2,000 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, due to a lack of clear guidelines, outdated practices and guidelines from previous eras are commonly misapplied to newer technologies. Most users and data providers 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 factors that influence the accuracy of mapping products derived from digital sensors.

# ANNEX 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 are applied in practice for a typical product with RMSE$_X$ and RMSE$_Y$ of 50 cm.

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

| Product Accuracy (RMSE$_H$) (cm) | A/T Accuracy | | Ground Control Accuracy | |
|---|---|---|---|---|
| | RMSE$_H$ (cm) | RMSE$_Z$ (cm) | RMSE$_H$ (cm) | RMSE$_Z$ (cm) |
| *50* | *25* | *50* | *25* | *50* |

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

| Product Accuracy (RMSE$_H$) (cm) | A/T Accuracy | | Ground Control Accuracy | |
|---|---|---|---|---|
| | RMSE$_H$ (cm) | RMSE$_Z$ (cm) | RMSE$_H$ (cm) | RMSE$_Z$ (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$_X$ and RMSE$_Y$ 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 provider, based on specific project needs and design criteria. This section provides some general guidance to assist in making that decision.

Example tables are provided to show the following: The general application of the standard as outlined in Section 7.3 (Table B.3); A cross reference to typical past associations between pixel size, map scale and the 1990 ASPRS legacy standard (Table B.4); and typical values associated with different levels of accuracy using current technologies (Table B.5).

Table B.3 presents examples of 24 horizontal accuracy classes and associated quality criteria as related to orthoimagery according to the formula and general requirements stated in Section 7.3.

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

| Horizontal Accuracy Class RMSE$_H$ (cm) | RMSE$_H$ (cm) | Orthoimage Mosaic Seamline Maximum Mismatch (cm) |
|---|---|---|
| 0.63 | 0.9 | 1.3 |
| 1.25 | 1.8 | 2.5 |
| 2.50 | 3.5 | 5.0 |
| 5.00 | 7.1 | 10.0 |
| 7.50 | 10.6 | 15.0 |
| 10.00 | 14.1 | 20.0 |
| 12.50 | 17.7 | 25.0 |
| 15.00 | 21.2 | 30.0 |
| 17.50 | 24.7 | 35.0 |
| 20.00 | 28.3 | 40.0 |
| 22.50 | 31.8 | 45.0 |
| 25.00 | 35.4 | 50.0 |
| 27.50 | 38.9 | 55.0 |
| 30.00 | 42.4 | 60.0 |
| 45.00 | 63.6 | 90.0 |
| 60.00 | 84.9 | 120.0 |
| 75.00 | 106.1 | 150.0 |
| 100.00 | 141.4 | 200.0 |
| 150.00 | 212.1 | 300.0 |
| 200.00 | 282.8 | 400.0 |
| 250.00 | 353.6 | 500.0 |
| 300.00 | 424.3 | 600.0 |
| 500.00 | 707.1 | 1000.0 |
| 1000.00 | 1414.2 | 2000.0 |

As outlined in Annex A, in the transition between hardcopy and softcopy mapping environments, user's and the mapping community established generally accepted associations between orthoimagery pixel size, final map scale and the ASPRS 1990 map accuracy classes. These associations are based primarily on relationships for scanned film, older technologies and legacy standards. While they may not directly apply to digital geospatial data produced with newer technologies, these practices have been in widespread use for many years and many existing data sets are based on these associations. As such, it is useful to have a cross reference relating these legacy specifications to their corresponding RMSE$_X$ and RMSE$_Y$ accuracy classes in the new standard.

Table B.4 lists the most common associations that have been established (based on user's interpretation and past technologies) to relate orthoimagery pixel size to map scale and the ASPRS 1990 legacy standard map accuracy classes.

**Table B.4 Examples on Horizontal Accuracy for Digital Orthoimagery**
**Interpreted from ASPRS 1990 Legacy Standard.**

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

| Common Orthoimagery Pixel Sizes | Associated Map Scale | ASPRS 1990 Accuracy Class | Associated Horizontal Accuracy According to Legacy ASPRS 1990 Standard | |
|---|---|---|---|---|
| | | | $RMSE_X$ $RMSE_Y$ (cm) | $RMSE_X$ and $RMSE_Y$ in terms of pixels |
| 0.625 cm | 1:50 | 1 | 1.3 | 2-pixels |
| | | 2 | 2.5 | 4-pixels |
| | | 3 | 3.8 | 6-pixels |
| 1.25 cm | 1:100 | 1 | 2.5 | 2-pixels |
| | | 2 | 5.0 | 4-pixels |
| | | 3 | 7.5 | 6-pixels |
| 2.5 cm | 1:200 | 1 | 5.0 | 2-pixels |
| | | 2 | 10.0 | 4-pixels |
| | | 3 | 15.0 | 6-pixels |
| 5 cm | 1:400 | 1 | 10.0 | 2-pixels |
| | | 2 | 20.0 | 4-pixels |
| | | 3 | 30.0 | 6-pixels |
| 7.5 cm | 1:600 | 1 | 15.0 | 2-pixels |
| | | 2 | 30.0 | 4-pixels |
| | | 3 | 45.0 | 6-pixels |
| 15 cm | 1:1,200 | 1 | 30.0 | 2-pixels |
| | | 2 | 60.0 | 4-pixels |
| | | 3 | 90.0 | 6-pixels |
| 30 cm | 1:2,400 | 1 | 60.0 | 2-pixels |
| | | 2 | 120.0 | 4-pixels |
| | | 3 | 180.0 | 6-pixels |
| 60 cm | 1:4,800 | 1 | 120.0 | 2-pixels |
| | | 2 | 240.0 | 4-pixels |
| | | 3 | 360.0 | 6-pixels |
| 1 meter | 1:12,000 | 1 | 200.0 | 2-pixels |
| | | 2 | 400.0 | 4-pixels |
| | | 3 | 600.0 | 6-pixels |
| 2 meter | 1:24,000 | 1 | 400.0 | 2-pixels |
| | | 2 | 800.0 | 4-pixels |
| | | 3 | 1,200.0 | 6-pixels |
| 5 meter | 1:60,000 | 1 | 1,000.0 | 2-pixels |
| | | 2 | 2,000.0 | 4-pixels |
| | | 3 | 3,000.0 | 6-pixels |

Given current sensor and processing technologies for large and medium format metric cameras, an orthoimagery accuracy of 1-pixel $RMSE_X$ and $RMSE_Y$ is considered achievable, assuming proper project design and best practices implementation. This level of accuracy is more stringent by a factor of two than orthoimagery accuracies typically associated with the ASPRS 1990 Class 1 accuracies presented in Table B.4.

Achieving the highest level of accuracy requires specialized consideration related to sensor type, ground control density, ground control accuracies, and overall project design. In many cases, this results in higher cost. 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 fact is particularly true for update 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 originally have been developed to a lower accuracy standard.

Table B.5 provides a general guideline to determine the appropriate orthoimagery accuracy class for three different levels of geospatial accuracy values listed as “highest accuracy work.” $RMSE_X$ and $RMSE_Y$ of 1-pixel (or better) are considered to reflect the highest tier accuracy class given current technologies. This accuracy class is appropriate when geospatial accuracies are of higher importance and when the higher accuracies are supported by sufficient sensor, ground control and digital terrain model accuracies. Values listed as “standard mapping and GIS work” specify a 2-pixel $RMSE_X$ and $RMSE_Y$ accuracy class. This accuracy is appropriate for a standard level of high quality and high accuracy geospatial mapping applications. It is equivalent to ASPRS 1990 Class 1 accuracies, as interpreted by users as industry standard and presented in Table B.4. This level of accuracy is typical of a large majority of existing projects designed to legacy standards. $RMSE_X$ and $RMSE_Y$ accuracies of 3 or more pixels would be considered appropriate for visualization and less accurate work when higher accuracies are not needed.

Users should be aware that the use of the symbol ≥ in Table B.5 is intended to infer that users can specify larger threshold values for $RMSE_X$ and $RMSE_Y$. The symbol ≤ in Table B.5 indicates that users can specify lower thresholds at such time as they may be supported by current or future technologies.

The orthoimagery pixel sizes and associated $RMSE_X$ and $RMSE_Y$ accuracy classes presented in Table B.5 are largely based on experience with current sensor technologies and primarily apply to large and medium format metric cameras. The table is only provided as a guideline for users during the transition period to the new standard. These associations may change in the future as mapping technologies continue to advance and evolve.

**Table B.5 Digital Orthoimagery Accuracy Examples for Current Large and Medium Format Metric Cameras**

| Common Orthoimagery Pixel Sizes | Recommended Horizontal Accuracy Class $RMSE_H$ (cm) | Orthoimage $RMSE_H$ in terms of pixels | Recommended Use4 |
|---|---|---|---|
| *1.25 cm* | *≤ 1.3* | *≤ 1 pixel* | *Highest accuracy work* |
| | *2.5* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 3.8* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *2.5 cm* | *≤ 2.5* | *≤ 1 pixel* | *Highest accuracy work* |
| | *5.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 7.5* | *≥ 3 pixels* | *Visualization and less accurate work* |

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[4] “Highest accuracy work” in Table B.5 refers only to the highest level of achievable accuracies relative to that specific resolution; it does not indicate “highest accuracy work” in any general sense. The final choice of both image resolution and final product accuracy class depends on specific project requirements and is the sole responsibility of the end user; this should be negotiated with the data provider and agreed upon in advance.

| | | | |
|---|---|---|---|
| *5 cm* | *≤ 5.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *10.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 15.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *7.5 cm* | *≤ 7.5* | *≤ 1 pixel* | *Highest accuracy work* |
| | *15.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 22.5* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *15 cm* | *≤ 15.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *30.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 45.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *30 cm* | *≤ 30.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *60.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 90.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *60 cm* | *≤ 60.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *120.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 180.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *1 meter* | *≤ 100.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *200.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 300.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *2 meter* | *≤ 200.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *400.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 600.0* | *≥ 3 pixels* | *Visualization and less accurate work* |
| *5 meter* | *≤ 500.0* | *≤ 1 pixel* | *Highest accuracy work* |
| | *1000.0* | *2 pixels* | *Standard Mapping and GIS work* |
| | *≥ 1500.0* | *≥ 3 pixels* | *Visualization and less accurate work* |

It should be noted that in tables B.4 and B.5, it is the pixel size of the final digital orthoimagery that is used to associate the horizontal accuracy class, not the Ground Sample Distance (GSD) of the raw image. When producing digital orthoimagery, the GSD as acquired by the sensor (and as computed at mean average terrain) should not be more than 95% of the final orthoimage pixel size. In extremely steep terrain, additional consideration may need to be given to the variation of the GSD across low lying areas to ensure that the variation in GSD across the entire image does not significantly exceed the target pixel size.

## B.3 Digital Planimetric Data Horizontal Accuracy Classes

Table B.6 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.6, 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 products accuracy. Different ranges may be considered in the future depending on future advances of such technologies and mapping practices.

**Table B.6 Horizontal Accuracy/Quality Examples for High Accuracy Digital Planimetric Data**

| ASPRS 2023 | | | Equivalent to Map Scale in | | Equivalent to Map Scale in NMAS |
|---|---|---|---|---|---|
| Horizontal Accuracy Class RMSEH (cm) | RMSEH (cm) | Approximate GSD of Source Imagery (cm) | ASPRS 1990 Class 1 | ASPRS 1990 Class 2 | |
| 0.63 | 0.9 | 0.31 to 0.63 | 1:25 | 1:12.5 | 1:16 |
| 1.25 | 1.8 | 0.63 to 1.25 | 1:50 | 1:25 | 1:32 |
| 2.5 | 3.5 | 1.25 to 2.5 | 1:100 | 1:50 | 1:63 |
| 5.0 | 7.1 | 2.5 to 5.0 | 1:200 | 1:100 | 1:127 |
| 7.5 | 10.6 | 3.8 to 7.5 | 1:300 | 1:150 | 1:190 |
| 10.0 | 14.1 | 5.0 to 10.0 | 1:400 | 1:200 | 1:253 |
| 12.5 | 17.7 | 6.3 to12.5 | 1:500 | 1:250 | 1:317 |
| 15.0 | 21.2 | 7.5 to 15.0 | 1:600 | 1:300 | 1:380 |
| 17.5 | 24.7 | 8.8 to 17.5 | 1:700 | 1:350 | 1:444 |
| 20.0 | 28.3 | 10.0 to 20.0 | 1:800 | 1:400 | 1:507 |
| 22.5 | 31.8 | 11.3 to 22.5 | 1:900 | 1:450 | 1:570 |
| 25.0 | 35.4 | 12.5 to 25.0 | 1:1000 | 1:500 | 1:634 |
| 27.5 | 38.9 | 13.8 to 27.5 | 1:1100 | 1:550 | 1:697 |
| 30.0 | 42.4 | 15.0 to 30.0 | 1:1200 | 1:600 | 1:760 |
| 45.0 | 63.6 | 22.5 to 45.0 | 1:1800 | 1:900 | 1:1,141 |
| 60.0 | 84.9 | 30.0 to 60.0 | 1:2400 | 1:1200 | 1:1,521 |
| 75.0 | 106.1 | 37.5 to 75.0 | 1:3000 | 1:1500 | 1:1,901 |
| 100.0 | 141.4 | 50.0 to 100.0 | 1:4000 | 1:2000 | 1:2,535 |
| 150.0 | 212.1 | 75.0 to 150.0 | 1:6000 | 1:3000 | 1:3,802 |
| 200.0 | 282.8 | 100.0 to 200.0 | 1:8,000 | 1:4000 | 1:5,069 |
| 250.0 | 353.6 | 125.0 to 250.0 | 1:10000 | 1:5000 | 1:6,337 |
| 300.0 | 424.3 | 150.0 to 300.0 | 1:12000 | 1:6000 | 1:7,604 |
| 500.0 | 707.1 | 250.0 to 500.0 | 1:20000 | 1:10000 | 1:21,122 |
| 1000.0 | 1414.2 | 500.0 to 1000.0 | 1:40000 | 1:20000 | 1:42,244 |

## B.4 Digital Elevation Data Vertical Accuracy Classes

Table B.7 provides vertical accuracy examples and other quality criteria for ten common vertical accuracy classes. Table B.8 compares the ten vertical accuracy classes with contours intervals from legacy ASPRS 1990 and NMAS 1947 standards. Table B.9 provides ten vertical accuracy classes with the recommended lidar point density suitable for each of them.

**Table B.7 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.8 Vertical Accuracy of the ASPRS 2023 Standard Compared with Legacy Standards**

| Vertical Accuracy Class | NVA (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.9 Examples of Vertical Accuracy and Recommended Lidar Point Density for Digital Elevation Data according to the ASPRS 2023 standard**

| *Vertical Accuracy Class* | *NVA (cm)* | *Recommended Minimum NPD[5] (pls/m2)* | *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 2023 Accuracy Values to Legacy ASPRS 1990 Accuracy Values

In this section, examples are provided for users who wish to relate this standard to the legacy ASPRS 1990 Accuracy Standards for Large-Scale Maps. A major advantage of this standard is that accuracy

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[5] 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/$m^2$). 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 1st (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 to best fit project requirements and complexity of surfaces to be modeled.

statements are based on RMSE at ground scale. The legacy standard refers to RMSE but defines Class 1 as higher accuracy and Classes 2 and 3 as lower accuracy, while this standard refers 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 accuracies values between this standard 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 2023 Standard to the Legacy ASPRS Map Standard of 1990***

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

Solution:

1. Because both standards utilize the same RMSE measure to express horizontal accuracy, then the accuracy of the map according to the legacy 1990 standard is $RMSE_X = RMSE_Y = 15$ cm
2. To find the equivalent map scale according to the legacy 1990 standard, follow the following steps:
    a. Multiply the $RMSE_X$ and $RMSE_Y$ value in centimeters by 40 to compute the map scale factor (MSF) for a Class 1 map:

       MSF = 15 (cm) x 40 = 600

    b. The map scale according to the legacy 1990 standard is:

       Scale = 1:MSF or 1:600 Class 1;

The accuracy value of $RMSE_X = RMSE_Y = 15$ cm is also equivalent to Class 2 accuracy for a map with a scale of 1:300.

***Example 2: Relating the Vertical Accuracy of an Elevation Data Set calculated with the ASPRS 2023 Standard to the to the Legacy ASPRS Map Standard of 1990***

Given an elevation data set with a vertical accuracy of $RMSE_V = 10$ cm according to the 2023 standard, compute the equivalent contour interval according to the legacy 1990 standard.

*Solution*:

The legacy ASPRS map standard of 1990 states:

> *"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 standard is:

$RMSE_V = 10$ cm

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

$CI = 3 * RMSE_Z = 3 * 10$ 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 standard, 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 2023 Accuracy Values to Legacy NMAS 1947 Accuracy Values

In this section, examples are provided for users who wish to relate this standard to the legacy National Map Accuracy Standard (NMAS) of 1947. Regarding horizontal accuracy, the legacy 1947 standard states:

> *"Horizontal Accuracy: For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch."*

The legacy 1947 standard uses 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 standard states:

> *"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 2023 standard and the legacy 1947 standard.

***Example 3: Relating the Horizontal Accuracy of a Map or Orthorectified Image calculated with the ASPRS 2023 Standard to the Legacy National Map Accuracy Standard of 1947***

Given a map or orthoimagery with an accuracy of $RMSE_X$ = $RMSE_Y$ = 15 cm according to the ASPRS 2023 standard, compute the equivalent accuracy and map scale according to the legacy 1947 standard.

*Solution*:

$RMSE_X$ = $RMSE_Y$= 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 1:20,00.

Use the factor "1/30 inch."

CMAS (CE90) = 2.1460 * $RMSE_X$ = 2.1460 * $RMSE_Y$

CE90 = 2.1460 * 15 cm= 32.19 cm

Convert CE90 to units of 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 2023 Standard to the Legacy National Map Accuracy Standard of 1947***

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

*Solution*:

As mentioned earlier, the legacy 1947 standard states 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 * $RMSE_z$ = 1.6449 * 10 cm = 16.449 cm

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

VMAS (LE90) = ½ CI, or

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

## B.7 Relating ASPRS 2023 Accuracy Values to the FGDC National Standard for Spatial Data Accuracy (NSSDA)

In this section, examples are provided for users who wish to relate this standard 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 2023 Standard to the FGDC National Standard for Spatial Data Accuracy (NSSDA)***

Given a map or orthoimagery with an accuracy of $RMSE_X$ = $RMSE_Y$ = 15 cm according to the ASPRS 2023 standard, compute the equivalent accuracy and map scale according to the FGDC National Standard for Spatial Data Accuracy (NSSDA).

*Solution*:

If $RMSE_X \approx RMSE_Y$, then according to NSSDA the horizontal positional accuracy is estimated at 95% confidence level using the following formula:

$Accuracy_{R95}$ = 2.4477 * $RMSE_X$= 2.4477 * $RMSE_Y$

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

and if $RMSE_X = RMSE_Y$ then

$$RMSE_R = \sqrt{2RMSE_X{}^2} = \sqrt{2RMSE_Y{}^2}$$

$$RMSE_R = 1.4142 * RMSE_X = 1.4142 * RMSE_Y$$

$$RMSE_X = RMSE_Y = \frac{RMSE_R}{1.4142}$$

$RMSE_R = 1.4142 * 15 = 21.21$ cm

$Accuracy_{R95} = 2.4477 * RMSE_R/1.4142 = 1.7308 * RMSE_R = 1.7308 * 21.21 = 37.71$ cm

***Example 6: Relating the Vertical Accuracy of an Elevation Data Set calculated with the ASPRS 2023 Standard 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 standard, 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:

$Accuracy_{V95} = 1.96 * RMSE_Z$

$Accuracy_{V95} = 1.96 * 10 = 19.60$ 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 increasing with flying height. These are not the only contributing factors to horizontal error, but this type of estimate is helpful when planning data acquisition when 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 10.0 arc-second (0.0027 degrees, ) for roll and pitch and 15.0 arc-second (0.00417 degree) in heading, Table B.10 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.10 Estimated Horizontal Error ($RMSE_H$) as a Function of GNSS Error, IMU Error, and Flying Height**

| FH (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.10 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 accuracies 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 properly controlled, calibrated, boresighted, and processed. Errors introduced during any of these steps will affect the accuracy of the data, regardless of how dense the data are. That said, high density lidar data are 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. The use of denser data for complex surface representation does not make the individual lidar measurements any more accurate, but it does improve the accuracy of the derived surface at locations between the lidar measurements (as each gap between points is smaller).

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 vegetation to the ground. More ground points will result more accurate interpolation between points and improved surface definition because more points on the actual ground surface are being measured. 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.

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, by better detection of edges for breaklines and by increasing the confidence of the relative accuracy in swath overlap areas through the reduction of interpolation existing within the data set. High density 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.

# ANNEX C — ACCURACY TESTING AND REPORTING GUIDELINES (NORMATIVE)

## C.1 Checkpoint Requirements

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

The total number of points and 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 did not define or characterize spatial distribution of the points. A quantitative methodology for characterization and specification of the spatial distribution of checkpoints, accounting for land cover type and project shape, does not currently exist. ASPRS encourages research into this topic for future revisions of this Standard. In the interim, this Annex provides general recommendations and guidelines for number and placements of checkpoints for accuracy assessment.

## C.2 Accuracy of Checkpoints

According to this standard, 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 * RMSE should be investigated.

## C.3 Number of Checkpoints

Table C.1 lists ASPRS recommendations for the number of checkpoints to be used for horizontal accuracy testing of digital orthoimagery and planimetric data sets and for vertical accuracy of elevation data. The project area should be divided based on land cover into non-vegetated and vegetated, and the appropriate number of checkpoints acquired to test horizontal accuracy of digital orthophotos and planimetric data, as well as vertical accuracy of elevation data, for the non-vegetated area. Additional checkpoints should be acquired to evaluate vertical accuracy of elevation data in vegetated areas.

To illustrate the use of Table C.1, consider a project area comprising a total area of 1,500 km$^2$; with heavy vegetation covers approximately 500 km$^2$and the remaining 1000 km$^2$is non-vegetated. From Table C.1, 40 checkpoints are recommended to test both horizontal accuracy of digital orthoimagery and/or planimetric data sets and the vertical accuracy of elevation data in the non-vegetated area. From Table C.2, 30 checkpoints are recommended to test the vertical accuracy of elevation data in the vegetated area. A total of 70 checkpoints is recommended to assess horizontal and vertical accuracy of all project deliverables.

**Table C.1 Recommended Number of Checkpoints Based on Area**

| Area (km$^2$) | Number of Checkpoints |
|---|---|
| *≤500* | *30* |
| *501-750* | *35* |
| *751-1000* | *40* |
| *1001-1250* | *45* |
| *1251-1500* | *50* |
| *1501-1750* | *55* |
| *1751-2000* | *60* |

| | |
|---|---|
| *2001-2250* | *65* |
| *2251-2500* | *70* |

Using metric units, ASPRS recommends 140 static vertical checkpoints (70 for NVA and 70 for VVA) for the first 2500 km$^2$ area within a project, which provides a statistically defensible number of samples on which to base a valid vertical accuracy assessment.

For horizontal testing of areas >2500 km$^2$, clients should determine the number of additional horizontal checkpoints, if any, based on criteria such as resolution of imagery and extent of urbanization.

For vertical testing of areas >2500 km$^2$, add 5 additional vertical checkpoints for each additional 500 km$^2$ area of the non-vegetated area of the project to evaluate the NVA. Similarly, add 5 additional vertical checkpoints for each additional 500 km2 area of the vegetated area of the project to evaluate the VVA. The recommended number and distribution of NVA and VVA checkpoints may vary depending on the importance of different land cover categories and client requirements.

## 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 area of the project. There may be exceptions depending on the nature of the terrain and land cover; however, best efforts should be made to assure that the best possible distribution of the checkpoints is achieved.

ASPRS recognizes that some project areas are primarily non-vegetated, whereas other areas are primarily vegetated. For these reasons, the distribution of checkpoints can vary based on the general proportion of vegetated and non-vegetated area in the project. Checkpoints should be distributed generally proportionally among the various vegetated land cover types in the project.

## C.5 NSSDA Methodology for Checkpoint Distribution (Horizontal and Vertical Testing)

NSSDA offers a method that can be applied to projects that are generally rectangular in shape and are largely non-vegetated; these methods are difficult to apply to the irregular shapes of many projects or to most vegetated land cover types.

FGDC (1998) specifies the following:

*“Due to the diversity of user requirements for digital geospatial data and maps, it is not realistic to include statements in this standard that specify the spatial distribution of checkpoints. Data and/or map producers must determine checkpoint locations.*

*Checkpoints may be distributed more densely in the vicinity of important features and more sparsely in areas that are of little or no interest. When data exist for only a portion of the data set, confine test points to that area. When the distribution of error is likely to be nonrandom, it may be desirable to locate checkpoints to correspond to the error distribution.*

*For a data set covering a rectangular area that is believed to have uniform positional accuracy, checkpoints may be distributed so that points are spaced at intervals of at least 10% of the diagonal distance across the data set and at least 20% of the points are located in each quadrant of the data set.”*

ASPRS recommends that, where appropriate and to the highest degree possible, the NSSDA method be applied to the project and incorporate the two main cover type areas, vegetated versus non-vegetated.

In some areas, access restrictions may prevent the desired spatial distribution of checkpoints across land cover types; difficult terrain and transportation limitations may make some land cover type areas practically inaccessible. Where it is not geometrically or practically applicable to strictly apply the NSSDA method, data vendors should use their best professional judgment to apply the spirit of that method in selecting locations for checkpoints.

The recommendations in sections C.1 through C.3 offer a good deal of discretion in the location and distribution of checkpoints, and this is intentional. 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 between and agreed upon by the vendor and customer as part of the project plan.

## C.6 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 a parking lot where a car may be parked during aerial data acquisition. The choice of surveying equipment and methodology should be based upon accuracy needs of the final product; surveying guidelines and best practices 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.7 Horizontal Checkpoints for Elevation Data

Elevation data sets do not always contain the type of well-defined points that are required for horizontal testing to NSSDA specifications. Specific methods for testing and verifying horizontal accuracies of elevation data sets depend on technology used and project design. The specific testing methodology used 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 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, allowing them to double 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 provider has the responsibility to establish appropriate methodologies, applicable to the technologies used, to verify that horizontal accuracies meet the stated requirements.

Testing the horizontal accuracy of lidar data is not always performed as it is often difficult. In most cases, users trust the lidar system manufacturer’s estimation of horizontal accuracy. 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.8 Testing and Reporting of Product Accuracy

New in this 2nd Edition of the ASPRS Positional Accuracy Standard for Geospatial Data, is inclusion of checkpoint error in the final computation of the product accuracy. Mapping technologies today are capable of producing data 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 checkpoints surveying. The latter error results in erroneous datum estimation. To accurately compute product's accuracy, the two error sources should be considered, the error from the mathematical modeling and calibration and the error in the datum estimation due to inaccurate ground control or checkpoints. The following formula represents the new and correct method of computing a product accuracy:

$$Horizontal\ Product\ Accuracy = \sqrt{{RMSE_{H1}}^2 + {RMSE_{H2}}^2}$$

$$Vertical\ Product\ Accuracy = \sqrt{{RMSE_{V1}}^2 + {RMSE_{V2}}^2}$$

Where:

$RMSE_{H1}$ and $RMSE_{V1}$ are the components of error derived from product fit to the checkpoints.

$RMSE_{H2}$ and $RMSE_{V2}$ 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 $RMSE_{V2}$ = 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 $RMSE_{V1}$ = 1 cm.

Using the formula above:

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

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

### *C.8.1 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, assuming that the horizontal errors are normally distributed, the sample size 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 the pointing errors; a zoom level that results in sub-pixel pointing accuracy is desirable. It 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 ASPRS horizontal accuracy class of 20 cm. Also 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 the following:

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

In this case, the product accuracy is better than the "tested to meet" accuracy, because measurement error was introduced during the testing process. If "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.8.2 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 assuming that the vertical errors are normally distributed, the sample size sufficiently large, and the mean error is sufficiently small.

VVA should also be computed as $RMSE_V$ with care taken to evaluating skew and kurtosis; skewed results may occur in vegetated areas due to the low density of lidar point cloud and the degraded quality of GPS survey 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 for reasons discussed elsewhere in this standard. This standard relies primarily on lidar performance in open and unobscured terrain when evaluating data accuracy and quality.

## C.10 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 NVA and VVA accuracies; areas not delineated by an obscure area polygon are presumed 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 being created using two common paradigms. 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 detailed technique is clearly 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 as to cause the project to look worse than it really 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 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 certain cases, too small an area will "checker board" the low confidence areas; in other cases too large an area will not adequately delineate low confidence areas. Determination of the minimum size of low confidence polygons should be a function of the topography, land cover, and final use 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 Ground Point Density, Max NGPS: Maximum 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*<br>*[≤ 0.22]* | *≥ 5*<br>*[≤ 0.45]* | *0.67* | *0.5*<br>*[2,000]* |
| *2.5-cm* | *≥ 16*<br>*[≤ 0.25]* | *≥ 4*<br>*[≤ 0.50]* | *0.75* | *1*<br>*[4,000]* |
| *5-cm* | *≥ 8*<br>*[≤ 0.35]* | *≥ 2*<br>*[≤ 0.71]* | *1.06* | *2*<br>*[8,000]* |
| *10-cm* | *≥ 2*<br>*[≤ 0.71]* | *≥ 0.5*<br>*[≤ 1.41]* | *2.12* | *5*<br>*[20,000]* |

| | | | | |
|---|---|---|---|---|
| *15-cm* | *≥ 1.0*<br>*[≤ 1.0]* | *≥ 0.25*<br>*[≤ 2.0]* | *3.0* | *5*<br>*[20,000]* |
| *20-cm* | *≥ 0.5*<br>*[≤ 1.4]* | *≥ 0.125*<br>*[≤ 2.8]* | *4.24* | *5*<br>*[20,000]* |
| *33.3-cm* | *≥ 0.25*<br>*[≤ 2.0]* | *≥ 0.0625*<br>*[≤ 4.0]* | *6.0* | *10*<br>*[40,000]* |
| *66.7-cm* | *≥ 0.1*<br>*[≤ 3.2]* | *≥ 0.025*<br>*[≤ 6.3]* | *9.5* | *15*<br>*[60,000]* |
| *100-cm* | *≥ 0.05*<br>*[≤ 4.5]* | *≥ 0.0125*<br>*[≤ 8.9]* | *13.4* | *20*<br>*[80,000]* |
| *333.3-cm* | *≥ 0.01*<br>*[≤ 10.0]* | *≥ 0.0025*<br>*[≤ 20.0]* | *30.0* | *25*<br>*[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 distinctly different types of low confidence areas:

- The first type is identified by the data producer in advance, indicating where acceptable representation of bare earth is expected to be unlikely or impossible. 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 such advance delineation.
- The second type occurs in valid VVA areas, such as forests that would traditionally be depicted with dashed contours, but where checkpoints *should* be surveyed and accuracy assessment *should* be performed. Such low confidence areas are delineated subsequent to classification and would usually be identifiable by the notable low density of bare-earth points.

Low confidence polygons allow lidar data providers to protect themselves from unusable/unfair checkpoints in swamps and protect the customer from data providers who might try to alter their data. 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.11 Erroneous Checkpoints

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

- If it is demonstrated, with pictures and descriptions, that the checkpoint was improperly located, such as a vertical checkpoint 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 were 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.

## C.12 Data Internal Precision Assessment

To the greatest extent possible, data internal precision testing locations 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 and urban areas).
- 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.13 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).

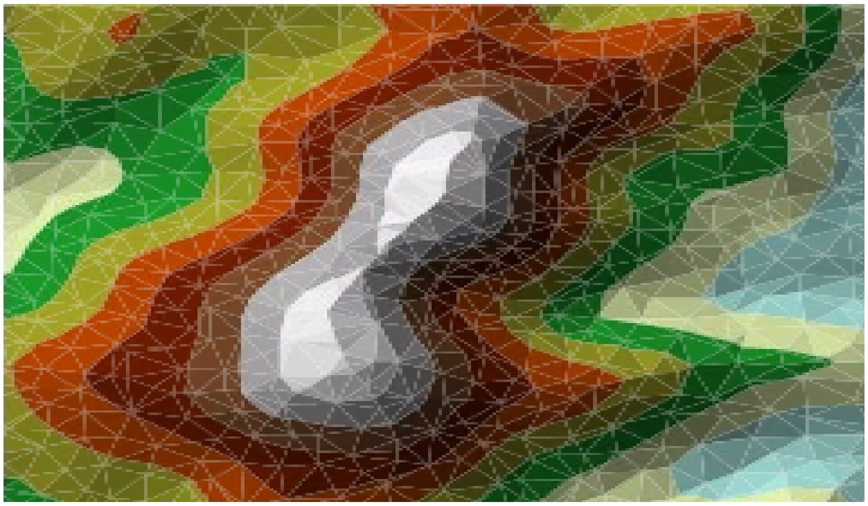


**Figure C.1 Topographic Surface Represented as a TIN**

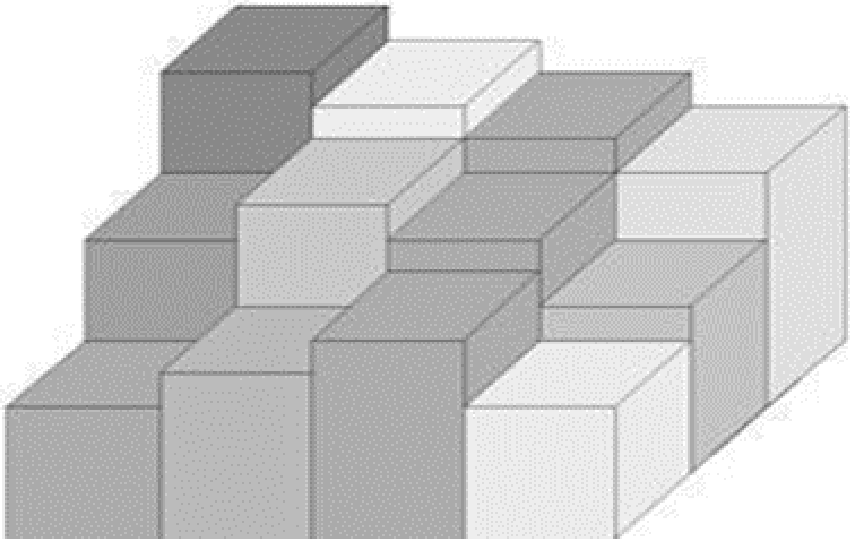


**Figure C.2 Topographic Surface Represented as a DEM**

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 creating a TIN from the point-based elevation data set and 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 could be addressed by future versions of this standard 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 is 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 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 metadata and 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.

# ANNEX D — ACCURACY STATISTICS AND EXAMPLE (NORMATIVE)

## D.1 NSSDA Reporting Accuracy Statistics

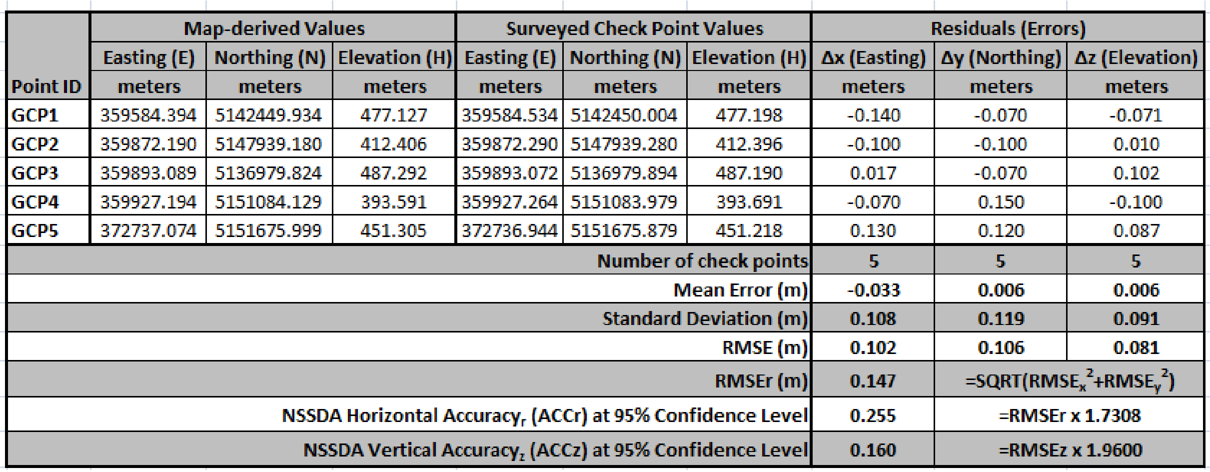
The National Standard for Spatial Data Accuracy (NSSDA) documents the equations for computation of $RMSE_X$, $RMSE_Y$, $RMSE_R$ and $RMSE_Z$, as well as horizontal (radial) and vertical accuracies at the 95% confidence levels, $Accuracy_R$ and $Accuracy_Z$, respectively. These statistics assume that errors approximate a normal error distribution and that the mean error is small relative to the target accuracy. The ASPRS Positional Accuracy Standard for Geospatial Data reporting methodology differs from the NSSDA reporting methodology because it includes error inherited from ground control and checkpoints when computing the final accuracy product accuracy, as discussed in Annex C.

### D.1.1 NSSDA Accuracy Computations

For the purposes of demonstration, suppose you have five checkpoints to use to verify the final horizontal and vertical accuracy for a data set (fewer than the 30 checkpoints required by this standard are used for brevity of the example).

Table D.1 provides the map-derived coordinates and the surveyed coordinated 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 horizontal accuracy class with a maximum $RMSE_X = RMSE_Y$ = 15 cm and a vertical accuracy class of $RMSE_Z$ = 10 cm.

**Table D.1 NSSDA Accuracy Statistics for Example Data**



| | Map-derived Values | | | Surveyed Check Point Values | | | Residuals (Errors) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Easting (E) | Northing (N) | Elevation (H) | Easting (E) | Northing (N) | Elevation (H) | Δx (Easting) | Δy (Northing) | Δz (Elevation) |
| Point ID | meters | meters | meters | meters | meters | meters | meters | meters | meters |
| 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 |
| RMSEr (m) | | | | | | | 0.147 | =SQRT($RMSE_x^2$+$RMSE_y^2$) | |
| NSSDA Horizontal $Accuracy_r$ (ACCr) at 95% Confidence Level | | | | | | | 0.255 | =RMSEr x 1.7308 | |
| NSSDA Vertical $Accuracy_z$ (ACCz) at 95% Confidence Level | | | | | | | 0.160 | =RMSEz x 1.9600 | |

### *Computation of Mean Errors in X, Y, and Z*

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

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

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 Root Mean Square Error:***

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

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,

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

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

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

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

$$RMSE_R = \sqrt{{RMSE_x}^2 + {RMSE_y}^2}$$

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

### ***Computation of NSSDA Accuracy at 95% Confidence Level***

(Note: There are no significant systematic biases in the measurements. The mean errors are all smaller than 25% of the specified RMSE in Northing, Easting, and Elevation.)

Positional Horizontal Accuracy at 95% Confidence Level =

$$2.4477\left(\frac{RMSE_R}{1.4142}\right) = 1.7308(RMSE_R) = 1.7308\ (0.147) = 0.255 \text{ m}$$

Vertical Accuracy at 95% Confidence Level =

$$1.9600(RMSE_z) = 1.9600(0.081) = 0.160 \text{ m}$$