APPENDIX C

ASPRS Positional Accuracy Standards for Digital Geospatial Data (Reprint)

ASPRS Positional Accuracy Standards for Digital Geospatial Data

(EDITION 1, VERSION 1.0. - NOVEMBER, 2014)

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FOREWORD

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

1. PURPOSE

The objective of the *ASPRS Positional Accuracy Standards for Digital Geospatial Data* is to replace the existing *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 the higher accuracies achievable with newer technologies. The standard also includes additional accuracy measures, such as orthoimagery seam lines, aerial triangulation accuracy, lidar relative swath-to-swath accuracy, recommended minimum Nominal Pulse Density (NPD), horizontal accuracy of elevation data, delineation of low confidence areas for vertical data, and the required number and spatial distribution of checkpoints based on project area.

1.1 Scope and Applicability

This standard addresses geo-location accuracies of geospatial products and it is not intended to cover classification accuracy of thematic maps. Further, the standard does not specify the best practices or methodologies needed to meet the accuracy thresholds stated herein. Specific requirements for the testing methodologies are specified as are some of the key elemental steps that are critical to the development of data if they are to meet these standards. However, it is the responsibility of the data provider to establish all final project design parameters, implementation steps and quality control procedures necessary to ensure the data meets final accuracy requirements.

The standard is intended to be used by geospatial data providers and users to specify the positional accuracy requirements for final geospatial products.

1.2 Limitations

This standard is limited in scope to addressing accuracy thresholds and testing methodologies for the most common mapping applications and to meet immediate shortcomings in the outdated 1990 and 2004 standards referenced above. While the standard is intended to be technology independent and broad based, there are several specific accuracy assessment needs that were identified but are not addressed herein at this time, including:

1. Methodologies for accuracy assessment of linear features (as opposed to well defined points);
2. Rigorous total propagated uncertainty (TPU) modeling (as opposed to – or in addition to – ground truthing against independent data sources);
3. Robust statistics for data sets that do not meet the criteria for normally distributed data and therefore cannot be rigorously assessed using the statistical methods specified herein;
4. Image quality factors, such as edge definition and other characteristics;
5. Robust assessment of checkpoint distribution and density;
6. Alternate methodologies to TIN interpolation for vertical accuracy assessment.

This standard is intended to be the initial component upon which future work can build. Additional supplemental standards or modules should be pursued and added by subject matter experts in these fields as they are developed and approved by the ASPRS.

At this time this standard does not reference existing international standards. International standards could be addressed in future modules or versions of this standard if needed.

1.3 Structure and Format

The standard is structured as follows: The primary terms and definitions, references, and requirements are stated within the main body of the standard, according to the ASPRS standards template and without extensive explanation or justification. Detailed supporting guidelines and background information are attached as 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 guidelines for statistical assessment and examples for computing vertical accuracy in vegetated and non-vegetated terrain.

2. CONFORMANCE

No conformance requirements are established for this standard.

3. REFERENCES

American Society for Photogrammetry and Remote Sensing (ASPRS), 2013. *ASPRS Accuracy Standards for Digital Geospatial Data (DRAFT)*, *PE&RS*, December 2013, pp 1073-1085.

American Society for Photogrammetry and Remote Sensing (ASPRS), 1990. ASPRS Accuracy Standards for Large-Scale Maps, URL: *http://www.asprs.org/a/society/committees/standards/1990_jul_1068-1070.pdf* (last date accessed: 22 January 2015)

American Society for Photogrammetry and Remote Sensing (ASPRS), 2004. ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data, URL: *http://www.asprs.org/a/society/committees/standards/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf* (last date accessed: 22 January 2015)

Dieck, R.H., 2007. *Measurement Uncertainty: Methods and Applications*, Instrument Society of America, Research Triangle Park, North Carolina, 277 pp.

Federal Geographic Data Committee, 1998. FGDC-STD-007.2-1998, Geospatial Positioning Accuracy Standards, Part 2: Standards for Geodetic Networks, FGDC, c/o U.S. Geological Survey, URL: *https://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2* (last date accessed: 22 January 2015)

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* (last date accessed: 22 January 2015).

National Digital Elevation Program (NDEP), 2004. *NDEP Guidelines for Digital Elevation Data*, URL: *http://www.ndep.gov/NDEP_Elevation_Guidelines_Ver1_10May2004.pdf* (last date accessed: 22 January 2015).

National Geodetic Survey (NGS), 1997. NOAA Technical Memorandum NOS NGS-58, V. 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* (last date accessed: 22 January 2015)

National Geodetic Survey (NGS), 2008. NOAA Technical Memorandum NOS NGS-59, V1.5: Guidelines for Establishing GPS-Derived Orthometric Heights, URL: *http://www.ngs.noaa.gov/PUBS_LIB/NGS592008069FINAL2.pdf* (last date accessed: 22 January 2015).

Additional informative references for other relevant and related guidelines and specifications are included in Annex A.

4. AUTHORITY

The responsible organization for preparing, maintaining, and coordinating work on this guideline is the American Society for Photogrammetry and Remote Sensing (ASPRS), Map Accuracy Standards Working Group, a joint committee formed by the Photogrammetric Applications Division, Primary Data Acquisition Division, and the Lidar Division. For further information, contact the Division Directors using the contact information posted on the ASPRS website, www.asprs.org.

5. TERMS AND DEFINITIONS

absolute accuracy – A measure that accounts for all systematic and random errors in a data set.

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.

blunder – A mistake resulting from carelessness or negligence.

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.

consolidated vertical accuracy (CVA) – Replaced by the term Vegetated Vertical Accuracy (VVA) in this standard, CVA is the term used by the NDEP guidelines for vertical accuracy at the 95th percentile in all land cover categories combined.

fundamental vertical accuracy (FVA) – Replaced by the term Non-vegetated Vertical Accuracy (NVA), in this standard, FVA is the term used by the NDEP guidelines for vertical accuracy at the 95% confidence level in open terrain only where errors should approximate a normal error distribution.

ground sample distance (GSD) – The linear dimension of a sample pixel's footprint on the ground. Within this document GSD is used when referring to the collection GSD of the raw image, assuming near-vertical imagery. The actual GSD of each pixel is not uniform throughout the raw image and varies significantly with terrain height and other factors. Within this document, GSD is assumed to be the value computed using the calibrated camera focal length and camera height above average horizontal terrain.

horizontal accuracy – The horizontal (radial) component of the positional accuracy of a data set with respect to a horizontal datum, at a specified confidence level.

inertial measurement unit (IMU) – The primary component of an INS. 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, comprised of 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 gyro 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.

local accuracy – The uncertainty in the coordinates of points with respect to coordinates of other directly connected, adjacent points at the 95% confidence level.

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 95% confidence level.

non-vegetated vertical accuracy (NVA) – The vertical accuracy at the 95% confidence level in non-vegetated open terrain, where errors should approximate a normal distribution.

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.

pixel resolution or pixel size – As used within this document, pixel size is the ground size of a pixel in a digital orthoimage, after all rectifications and resampling procedures.

positional error – The difference between data set coordinate values and coordinate values from an independent source of higher accuracy for identical points.

positional accuracy – The accuracy of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.

precision (repeatability) – The closeness with which measurements agree with each other, even though they may all contain a systematic bias.

relative accuracy – A measure of variation in point-to-point accuracy in a data set.

resolution – The smallest unit a sensor can detect or the smallest unit an orthoimage depicts. The degree of fineness to which a measurement can be made.

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 symmetry or asymmetry within a data set. Symmetric data will have skewness towards 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.

supplemental vertical accuracy (SVA) – Merged into the Vegetated Vertical Accuracy (VVA) in this standard, SVA is the NDEP guidelines term for reporting the vertical accuracy at the 95th percentile in each separate land cover category where vertical errors may not follow a normal error distribution.

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.

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) – An estimate of the vertical accuracy, based on the 95th percentile, in vegetated terrain where errors do not necessarily approximate a normal distribution.

vertical accuracy – The measure of the positional accuracy of a data set with respect to a specified vertical datum, at a specified confidence level or percentile.

For additional terms and more comprehensive definitions of the terms above, reference is made to the *Glossary of Mapping Sciences*; *Manual of Photogrammetry*, 6th edition; *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd edition; and/or the *Manual of Airborne Topographic Lidar*, all published by ASPRS.

6. SYMBOLS, ABBREVIATED TERMS, AND NOTATIONS

ACC_r – the horizontal (radial) accuracy at the 95% confidence level
ACC_z – the vertical linear accuracy at the 95% confidence level
ASPRS – American Society for Photogrammetry and Remote Sensing
CVA – Consolidated Vertical Accuracy
DEM – Digital Elevation Model
DTM – Digital Terrain Model
FVA – Fundamental Vertical Accuracy
GSD – Ground Sample Distance
GNSS - Global Navigation Satellite System
GPS – Global Positioning System
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
$RMSE_r$ – the horizontal linear RMSE in the radial direction that includes both x- and y-coordinate errors.
$RMSE_x$ – the horizontal linear RMSE in the X direction (Easting)
$RMSE_y$ – the horizontal linear RMSE in the Y direction (Northing)
$RMSE_z$ – the vertical linear RMSE in the Z direction (Elevation)
RMSE – root-mean-square-error
$RMSD_z$ – root-mean-square-difference in elevation (z)
SVA – Supplemental Vertical Accuracy
TIN – Triangulated Irregular Network
VVA – Vegetated Vertical Accuracy
$\bar{x}$ – sample mean error, for x
s – sample standard deviation
γ_1 – sample skewness
γ_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.

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 Annex C, Section C.11 for detailed guidance on interpolation methods.

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 and checkpoint accuracies and processes should be established based on project requirements. Unless specified to the contrary, it is expected that all ground control and checkpoints should normally follow the guidelines for network accuracy as detailed in the Geospatial Positioning Accuracy Standards, Part 2: Standards for Geodetic Networks, Federal Geodetic Control Subcommittee, Federal Geographic Data Committee (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 Horizontal and Vertical Accuracies

Horizontal accuracy is to be assessed using root-mean-square-error (RMSE) statistics in the horizontal plane, i.e., $RMSE_x$, $RMSE_y$ and $RMSE_r$. Vertical accuracy is to be assessed in the z dimension only. For vertical accuracy testing, different methods are used in non-vegetated terrain (where errors typically follow a normal distribution suitable for RMSE statistical analyses) and vegetated terrain (where errors do not necessarily follow a normal distribution). When errors cannot be represented by a normal distribution, the 95th percentile value more fairly estimates accuracy at a 95% confidence level. For these reasons vertical accuracy is to be assessed using $RMSE_z$ statistics in non-vegetated terrain and 95th percentile statistics in vegetated terrain. Elevation data sets shall also be assessed for horizontal accuracy where possible, as outlined in Section 7.5.

With the exception of vertical data in vegetated terrain, error thresholds stated in this standard are presented in terms of the acceptable RMSE value. Corresponding estimates of accuracy at the 95% confidence level values are computed using *National Standard for Spatial Data Accuracy* (NSSDA) methodologies according to the assumptions and methods outlined in Annex D, Accuracy Statistics and Examples.

7.2 Assumptions Regarding Systematic Errors and Acceptable Mean Error

With the exception of vertical data in vegetated terrain, the assessment methods outlined in this standard, and in particular those related to computing NSSDA 95% confidence level estimates, 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 those requirements including an evaluation of statistical parameters such as the kurtosis, skew, and mean error, as well as removal of systematic errors or biases in order to achieve an acceptable mean error prior to delivery.

The exact specification of an acceptable value for mean error may vary by project and should be negotiated between the data provider and the client. As a general rule, these standards recommend that the mean error be less than 25% of the specified RMSE value for the project. If a larger mean error is negotiated as acceptable, this should be documented in the metadata. In any case, mean errors that are greater than 25% of the target RMSE, whether identified pre-delivery or post-delivery, should be investigated to determine the cause of the error and to determine what actions, if any, should be taken. These findings should be clearly documented in the metadata.

Where RMSE testing is performed, discrepancies between the x, y, or z coordinates of the ground point check survey and the data set that exceed three times the specified RMSE error threshold shall be interpreted as blunders and should be investigated and either corrected or explained before the data is considered to meet this standard. Blunders may not be discarded without proper investigation and explanation in the metadata.

7.3 Horizontal Accuracy Standards for Geospatial Data

Table 7.1 specifies the primary horizontal accuracy standard for digital data, including digital orthoimagery, digital planimetric data, and scaled planimetric maps. This standard defines horizontal accuracy classes in terms of their $RMSE_x$ and $RMSE_y$ values. While prior ASPRS standards used numerical ranks for discrete accuracy classes tied directly to map scale (i.e., Class 1, Class 2, etc.), many modern applications require more flexibility than these classes allowed. Furthermore, many applications of horizontal accuracy cannot be tied directly to compilation scale, resolution of the source imagery, or final pixel resolution.

A Scope of Work, for example, can specify that digital orthoimagery, digital planimetric data, or scaled maps must be produced to meet ASPRS Accuracy Standards for 7.5 cm $RMSE_x$ and $RMSE_y$ Horizontal Accuracy Class.

Annex B includes extensive examples that relate accuracy classes of this standard to their equivalent classes according to legacy standards. $RMSE_x$ and $RMSE_y$ recommendations for digital orthoimagery of various pixel sizes are presented in Table B.5. Relationships to prior map accuracy standards are presented in Table B.6. Table B.6 lists $RMSE_x$ and $RMSE_y$ recommendations for digital planimetric data produced from digital imagery at various GSDs and their equivalent map scales according to the legacy standards of ASPRS 1990 and NMAS of 1947. The recommended associations of $RMSE_x$ and $RMSE_y$, pixel size, and GSD that are presented in the above mentioned tables of Annex B are based on current status of mapping technologies and best practices. Such associations may change in the future as mapping technologies continue to advance and evolve.

7.4 Vertical Accuracy Standards for Elevation Data

Vertical accuracy is computed using RMSE statistics in non-vegetated terrain and 95th percentile statistics in vegetated terrain. The naming convention for each vertical accuracy class is directly associated with the RMSE expected from the product. Table 7.2 provides the vertical accuracy classes naming convention for any digital elevation data. Horizontal accuracy requirements for elevation data are specified and reported independent of the vertical accuracy requirements. Section 7.5 outlines the horizontal accuracy requirements for elevation data.

Annex B includes examples on typical vertical accuracy values for digital elevation data and examples on relating the vertical accuracy of this standard to the legacy map standards. Table B.7 of Annex B lists 10 common vertical accuracy classes and their corresponding accuracy

TABLE 7.1 HORIZONTAL ACCURACY STANDARDS FOR GEOSPATIAL DATA

Horizontal Accuracy Class	Absolute Accuracy			Orthoimagery Mosaic Seamline Mismatch (cm)
	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_r$ (cm)	Horizontal Accuracy at 95% Confidence Level (cm)	
X-cm	$\leq X$	$\leq 1.414*X$	$\leq 2.448*X$	$\leq 2*X$

TABLE 7.2 VERTICAL ACCURACY STANDARDS FOR DIGITAL ELEVATION DATA

Vertical Accuracy Class	Absolute Accuracy			Relative Accuracy (where applicable)		
	$RMSE_z$ Non-Vegetated (cm)	NVA[1] at 95% Confidence Level (cm)	VVA[2] at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Vegetated Terrain ($RMSD_z$) (cm)	Swath-to-Swath Non-Vegetated Terrain (Max Diff) (cm)
X-cm	$\leq X$	$\leq 1.96*X$	$\leq 3.00*X$	$\leq 0.60*X$	$\leq 0.80*X$	$\leq 1.60*X$

values and other quality measures according to this standard. Table B.8 of Annex B provides the equivalent vertical accuracy measures for the same ten classes according to the legacy standards of ASPRS 1990 and NMAS of 1947. Table B.9 provides examples on vertical accuracy and the recommended lidar points density for digital elevation data according to the new ASPRS 2014 standard.

The Non-vegetated Vertical Accuracy at the 95% confidence level in non-vegetated terrain (NVA) is approximated by multiplying the accuracy value of the Vertical Accuracy Class (or $RMSE_z$) by 1.9600. This calculation includes survey checkpoints located in traditional open terrain (bare soil, sand, rocks, and short grass) and urban terrain (asphalt and concrete surfaces). The NVA, based on an $RMSE_z$ multiplier, should be used only in non-vegetated terrain where elevation errors typically follow a normal error distribution. $RMSE_z$-based statistics should not be used to estimate vertical accuracy in vegetated terrain or where elevation errors often do not follow a normal distribution.

The Vegetated Vertical Accuracy at the 95% confidence level in vegetated terrain (VVA) is computed as the 95th percentile of the absolute value of vertical errors in all vegetated land cover categories combined, including tall weeds and crops, brush lands, and fully forested areas. For all vertical accuracy classes, the VVA standard is 3.0 times the accuracy value of the Vertical Accuracy Class.

Both the $RMSE_z$ and 95th percentile methodologies specified above are currently widely accepted in standard practice and have been proven to work well for typical elevation data sets derived from current technologies. However, both methodologies have limitations, particularly when the number of checkpoints is small. As more robust statistical methods are developed and accepted, they will be added as new Annexes to supplement and/or supersede these existing methodologies.

7.5 Horizontal Accuracy Requirements for Elevation Data

This standard specifies horizontal accuracy thresholds for two types of digital elevation data with different horizontal accuracy requirements:

- **Photogrammetric Elevation Data:** For elevation data derived using stereo photogrammetry, the horizontal accuracy equates to the horizontal accuracy class that would apply to planimetric data or digital orthoimagery produced from the same source imagery, using the same aerial triangulation/INS solution.
- **Lidar Elevation Data:** Horizontal error in lidar derived elevation data is largely a function of positional error as derived from the Global Navigation Satellite System (GNSS), attitude (angular orientation) error (as derived from the INS) and flying altitude; and can be estimated based on these parameters. The following equation[3] provides an estimate for the horizontal accuracy for the lidar-derived data set assuming that the positional accuracy of the GNSS, the attitude accuracy of the Inertial Measurement Unit (IMU) and the flying altitude are known:

$$Lidar\ Horizontal\ Error\left(RMSE_r\right) = \sqrt{\left(GNSS\ positional\ error\right)^2 + \left(\frac{\tan(IMU\ error)}{0.55894170} x\ flying\ altitude\right)^2}$$

The above equation considers flying altitude (in meters), GNSS errors (radial, in cm), IMU errors (in decimal degrees), and other factors such as ranging and timing errors (which is estimated to be equal to 25% of the orientation errors). In the above equation, the values for the "GNSS positional error" and the "IMU error" can be derived from published manufacturer specifications for both the GNSS receiver and the IMU.

If the desired horizontal accuracy figure for lidar data is agreed upon, then the following equation can be used to estimate the flying altitude:

$$Flying\ Altitude = \frac{0.55894170}{\tan(IMU\ error)}\sqrt{(Lidar\ Horizontal\ Error\ (RMSEr))^2 - (GNSS\ positional\ error)^2}$$

Table B.10 can be used as a guide to estimate the horizontal errors to be expected from lidar data at various flying altitudes, based on estimated GNSS and IMU errors.

[1] Statistically, in non-vegetated terrain and elsewhere when elevation errors follow a normal distribution, 68.27% of errors are within one standard deviation (s) of the mean error, 95.45% of errors are within (2 * s) of the mean error, and 99.73% of errors are within (3 * s) of the mean error. The equation (1.9600 * s) is used to approximate the maximum error either side of the mean that applies to 95% of the values. Standard deviations do not account for systematic errors in the data set that remain in the mean error. Because the mean error rarely equals zero, this must be accounted for. Based on empirical results, if the mean error is small, the sample size sufficiently large and the data is normally distributed, 1.9600 * RMSE, is often used as a simplified approximation to compute the NVA at a 95% confidence level. This approximation tends to overestimate the error range as the mean error increases. A precise estimate requires a more robust statistical computation based on the standard deviation and mean error. ASPRS encourages standard deviation, mean error, skew, kurtosis and RMSE to all be computed in error analyses in order to more fully evaluate the magnitude and distribution of the estimated error.

[2] VVA standards do not apply to areas previously defined as low confidence areas and delineated with a low confidence polygon (see Appendix C). If VVA accuracy is required for the full data set, supplemental field survey data may be required within low confidence areas where VVA accuracies cannot be achieved by the remote sensing method being used for the primary data set.

[3] 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).

Guidelines for testing the horizontal accuracy of elevation data sets derived from lidar are outlined in Annex C.

Horizontal accuracies at the 95% confidence level, using NSSDA reporting methods for either "produced to meet" or "tested to meet" specifications should be reported for all elevation data sets.

For technologies or project requirements other than as specified above for photogrammetry and airborne lidar, appropriate horizontal accuracies should be negotiated between the data provider and the client. Specific error thresholds, accuracy thresholds or methods for testing will depend on the technology used and project design. The data provider has the responsibility to establish appropriate methodologies, applicable to the technologies used, to verify that horizontal accuracies meet the stated project requirements.

7.6 Low Confidence Areas for Elevation Data

If the VVA standard cannot be met, low confidence area polygons shall be developed and explained in the metadata. For elevation data derived from imagery, the low confidence areas would include vegetated areas where the ground is not visible in stereo. For elevation data derived from lidar, the low confidence areas would include dense cornfields, mangrove or similar impenetrable vegetation. The low confidence area polygons are the digital equivalent to using dashed contours in past standards and practice. Annex C, Accuracy Testing and Reporting Guidelines, outlines specific guidelines for implementing low confidence area polygons.

7.7 Accuracy Requirements for Aerial Triangulation and INS-based Sensor Orientation of Digital Imagery

The quality and accuracy of the aerial triangulation (if performed) and/or the Inertial Navigation System-based (INS-based) sensor orientations (if used for direct orientation of the camera) play a key role in determining the final accuracy of imagery derived mapping products.

For photogrammetric data sets, the aerial triangulation and/or INS-based direct orientation accuracies must be of higher accuracy than is needed for the final, derived products.

For INS-based direct orientation, image orientation angles quality shall be evaluated by comparing checkpoint coordinates read from the imagery (using stereo photogrammetric measurements or other appropriate method) to the coordinates of the checkpoint as determined from higher accuracy source data .

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

1. By comparing the values of the coordinates of the checkpoints as computed in the aerial triangulation solution to the coordinates of the checkpoints as determined from higher accuracy source data;
2. By comparing the values of the coordinates read from the imagery (using stereo photogrammetric measurements or other appropriate method) to the coordinates of the checkpoint as determined from higher accuracy source data.

For projects providing deliverables that are only required to meet accuracies in x and y (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:

- Accuracy of aerial triangulation designed for digital planimetric data (orthoimagery and/or digital planimetric map) **only**:

  $RMSE_{x(AT)}$ or $RMSE_{y(AT)} = ½ * RMSE_{x(Map)}$ or $RMSE_{y(Map)}$

  $RMSE_{x(AT)} = RMSE_{x(Map)}$ or $RMSE_{y(Map)}$ of orthoimagery

  Note: The exact contribution of aerial triangulation errors in z to the overall horizontal error budget for the products depends on ground point location in the image and other factors. The relationship stated here for an $RMSE_z$ (AT) of twice the allowable RMSE in x or y is a conservative estimate that accommodates the typical range of common camera geometries and provides allowance for many other factors that impact the horizontal error budget.
- Accuracy of aerial triangulation designed for elevation data, or planimetric data (orthoimagery and/or digital planimetric map) and elevation data production:

  $RMSE_{x(AT)}$, $RMSE_{y(AT)}$ or $RMSE_{z(AT)} = ½ * RMSE_{x(Map)}$, $RMSE_{y(Map)}$ or $RMSE_{z(DEM)}$

Annex B, Data Accuracy and Quality Examples, provides practical examples of these requirements.

7.8 Accuracy Requirements for Ground Control Used for Aerial Triangulation

Ground control points used for aerial triangulation should have higher accuracy than the expected accuracy of derived products according to the following two categories:

- Accuracy of ground control designed for planimetric data (orthoimagery and/or digital planimetric map)production **only**:

  $RMSE_x$ or $RMSE_y = 1/4 * RMSE_{x(Map)}$ or $RMSE_{y(Map)}$,

  $RMSE_z = 1/2 * RMSE_{x(Map)}$ or $RMSE_{y(Map)}$
- Accuracy of ground control designed for elevation data, or planimetric data **and** elevation data production:

  $RMSE_x$, $RMSE_y$ or $RMSE_z = 1/4 * RMSE_{x(Map)}$, $RMSE_{y(Map)}$ or $RMSE_{z(DEM)}$

Annex B, Data Accuracy and Quality Examples, provides practical examples of these requirements.

7.9 Checkpoint Accuracy and Placement Requirements

The independent source of higher accuracy for checkpoints shall be at least three times more accurate than the required accuracy of the geospatial data set being tested.

Horizontal checkpoints shall be established shall be established at well-defined points. A well-defined point represents a feature for which the horizontal position can be measured to a high degree of accuracy and position with respect to the geodetic datum. For the purpose of accuracy testing, well-defined points must be easily visible or identifiable on the ground, on the independent source of higher accuracy, and on the product itself. For testing orthoimagery, well-defined points shall not be selected on features elevated with respect to the elevation model used to rectify the imagery.

Unlike horizontal checkpoints, vertical checkpoints are not necessarily required to be clearly defined or readily identifiable point features.

Vertical checkpoints shall be established at locations that minimize interpolation errors when comparing elevations interpolated from the data set to the elevations of the checkpoints. Vertical checkpoints shall be surveyed on flat or uniformly-sloped open terrain and with slopes of 10% or less and should avoid vertical artifacts or abrupt changes in elevation.

7.10 Checkpoint Density and Distribution

When testing is to be performed, the distribution of the checkpoints will be project specific and must be determined by mutual agreement between the data provider and the end user. In no case shall an NVA, digital orthoimagery accuracy or planimetric data accuracy be based on less than 20 checkpoints.

A methodology to provide quantitative characterization and specification of the spatial distribution of checkpoints across the project extents, accounting for land cover type and project shape, is both realistic and necessary. But until such a methodology is developed and accepted, checkpoint density and distribution will be based primarily on empirical results and simplified area based methods.

Annex C, Accuracy Testing and Reporting Guidelines, provides details on the recommended checkpoint density and distribution. The requirements in Annex C may be superseded and updated as newer methods for determining the appropriate distribution of checkpoints are established and approved.

7.11 Relative Accuracy of Lidar and IFSAR Data

Relative accuracy assessment characterizes the internal geometric quality of an elevation data set without regard to surveyed ground control. The assessment includes two aspects of data quality: within-swath accuracy (smooth surface repeatability), and swath-to-swath accuracy. Within-swath accuracy is usually only associated with lidar collections. The requirements for relative accuracy are more stringent than those for absolute accuracy. Acceptable limits for relative accuracy are stated in Table 7.2.

For lidar collections, within-swath relative accuracy is a measure of the repeatability of the system when detecting flat, hard surfaces. Within-swath relative accuracy also indicates the internal stability of the instrument. Within-swath accuracy is evaluated against single swath data by differencing two raster elevation surfaces generated from the minimum and maximum point elevations in each cell (pixel), taken over small test areas of relatively flat, hard surfaces. The raster cell size should be twice the NPS of the lidar data. Suitable test areas will have produced only single return lidar points and will not include abrupt changes in reflectivity (e.g., large paint stripes, shifts between black asphalt and white concrete, etc.), as these may induce elevation shifts that could skew the assessment. The use of a difference test normalizes for the actual elevation changes in the surfaces. Acceptable thresholds for each accuracy class are based on the maximum difference between minimum and maximum values within each pixel.

For lidar and IFSAR collections, relative accuracy between swaths (swath-to-swath) in overlap areas is a measure of the quality of the system calibration/bore-sighting and airborne GNSS trajectories.

Swath-to-swath relative accuracy is assessed by comparing the elevations of overlapping swaths. As with within-swath accuracy assessment, the comparisons are performed in areas producing only single return lidar points. Elevations are extracted at checkpoint locations from each of the overlapping swaths and computing the root-mean-square-difference ($RMSD_z$) of the residuals. Because neither swath represents an independent source of higher accuracy, as used in $RMSE_z$ calculations, the comparison is made using the RMS differences rather than RMS errors. Alternatively, the so called "delta-z" raster file representing the differences in elevations can be generated from the subtraction of the two raster files created for each swath over the entire surface and it can be used to calculate the $RMSD_z$. This approach has the advantages of a more comprehensive assessment, and provides the user with a visual representation of the error distribution.

Annex C, Accuracy Testing and Reporting Guidelines, outlines specific criteria for selecting checkpoint locations for swath-to-swath accuracies. The requirements in the annex may be superseded and updated as newer methods for determining the swath-to-swath accuracies are established and approved.

7.12 Reporting

Horizontal and vertical accuracies shall be reported in terms of compliance with the RMSE thresholds and other quality and accuracy criteria outlined in this standard. In addition to the reporting stated below, ASPRS endorses and encourages additional reporting statements stating the estimated accuracy at a 95% confidence level in accordance with the FGDC NSSDA standard referenced in Section 3. Formulas for relating the RMSE thresholds in this standard to the NSSDA standard are provided in Annexes B and D.

If testing is performed, accuracy statements should specify that the data are "tested to meet" the stated accuracy.

If testing is not performed, accuracy statements should specify that the data are "produced to meet" the 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" method is appropriate for mature or established technologies where established procedures for project design, quality control and the evaluation of relative and absolute accuracies compared to ground control have been shown to produce repeatable and reliable results. Detailed specifications for testing and reporting to meet these requirements are outlined in Annex C.

The horizontal accuracy of digital orthoimagery, planimetric data, and elevation data sets shall be documented in the metadata in one of the following manners:

- "This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a ___ (cm) $RMSE_x$ / $RMSE_y$ Horizontal Accuracy Class. Actual positional accuracy was found to be $RMSE_x$ = ___ (cm) and $RMSE_y$ = ___ cm which equates to Positional Horizontal Accuracy = +/- ___ at 95% confidence level."[4]
- "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a ___ (cm) $RMSE_x$ / $RMSE_y$ Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- ___ cm at a 95% confidence level."[5]

The vertical accuracy of elevation data sets shall be documented in the metadata in one of the following manners:

- "This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a___ (cm) $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = ___ cm, equating to +/- ___ cm at 95% confidence level. Actual VVA accuracy was found to be +/- ___ cm at the 95th percentile."[4]
- "This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a ___ cm $RMSE_z$ Vertical Accuracy Class equating to NVA =+/-___cm at 95% confidence level and VVA =+/-___cm at the 95th percentile[5]

[4] "Tested to meet" is to be used only if the data accuracies were verified by testing against independent check points of higher accuracy.

[5] "Produced to meet" should be used by the data provider to assert that the data meets the specified accuracies, based on established processes that produce known results, but that independent testing against check points of higher accuracy was not performed.

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 Dataset (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 Dataset.
- In 2014, the latest USGS Lidar Base Specification Version 1.2 was published to accommodate lidar Quality Levels 0, 1, 2 and 3.

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:

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

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 Altitude	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)				Scanning Resolution (um)
Photo Scale	1" = 300'	1" = 600'	1" = 1200'	1" = 2400'	
	1:3,600	1:7,200	1:14,400	1:28,800	
Flying Altitude	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	21
	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. The majority of 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 ($RMSE_x$, $RMSE_y$) (cm)	A/T Accuracy		Ground Control Accuracy	
	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_z$ (cm)	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_z$ (cm)
50	25	50	12.5	25

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

Product Accuracy ($RMSE_x$, $RMSE_y$) (cm)	A/T Accuracy		Ground Control Accuracy	
	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_z$ (cm)	$RMSE_x$ and $RMSE_y$ (cm)	$RMSE_z$ (cm)
50	25	25	12.5	12.5

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.

As outlined in Annex A, in the transition between hardcopy and softcopy mapping environments, users 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 users interpretation and past technologies) to relate orthoimagery pixel size to map scale and the ASPRS 1990 legacy standard map accuracy classes.

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" specify an $RMSE_x$ and $RMSE_y$ accuracy class of 1-pixel (or better) and are considered to

Table B.3 Common Horizontal Accuracy Classes According to the New Standard[6]

Horizontal Accuracy Class $RMSE_r$ and $RMSE_z$ (cm)	$RMSE_r$ (cm)	Orthoimage Mosaic Seamline Maximum Mismatch (cm)	Horizontal Accuracy at the 95% Confidence Level (cm)
0.63	0.9	1.3	1.5
1.25	1.8	2.5	3.1
2.50	3.5	5.0	6.1
5.00	7.1	10.0	12.2
7.50	10.6	15.0	18.4
10.00	14.1	20.0	24.5
12.50	17.7	25.0	30.6
15.00	21.2	30.0	36.7
17.50	24.7	35.0	42.8
20.00	28.3	40.0	49.0
22.50	31.8	45.0	55.1
25.00	35.4	50.0	61.2
27.50	38.9	55.0	67.3
30.00	42.4	60.0	73.4
45.00	63.6	90.0	110.1
60.00	84.9	120.0	146.9
75.00	106.1	150.0	183.6
100.00	141.4	200.0	244.8
150.00	212.1	300.0	367.2
200.00	282.8	400.0	489.5
250.00	353.6	500.0	611.9
300.00	424.3	600.0	734.3
500.00	707.1	1000.0	1223.9
1000.00	1414.2	2000.0	2447.7

reflect the highest tier accuracy for the specified resolution 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 $RMSE_r$ and $RMSE_z$ 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. $RMSE_r$ and $RMSE_z$ 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 $RMSE_r$ and $RMSE_z$. 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 $RMSE_r$ and $RMSE_z$ 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.4 Examples on Horizontal Accuracy for Digital Orthoimagery Interpreted from ASPRS 1990 Legacy Standard

Common Orthoimagery Pixel Sizes	Associated Map Scale	ASPRS 1990 Accuracy Class	Associated Horizontal Accuracy According to Legacy ASPRS 1990 Standard	
			$RMSE_r$ and $RMSE_z$ (cm)	$RMSE_r$ and $RMSE_z$ 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

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 in order to ensure that the variation in GSD across the entire image does not significantly exceed the target pixel size.

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

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

Common Orthoimagery Pixel Sizes	Recommended Horizontal Accuracy Class: RMSE, and RMSE, (cm)	Orthoimage RMSE, and RMSE, in terms of pixels	Recommended use[1]
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
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
	1,000.0	2-pixels	Standard Mapping and GIS work
	≥1,500.0	≥3-pixels	Visualization and less accurate work

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. Different ranges may be considered in the future depending on future advances of such technologies and mapping practices.

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.

[1] "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.

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

ASPRS 2014				Equivalent to map scale in		
Horizontal Accuracy Class $RMSE_x$ and $RMSE_y$ (cm)	$RMSE_r$ (cm)	Horizontal Accuracy at the 95% Confidence Level (cm)	Approximate GSD of Source Imagery (cm)	ASPRS 1990 Class 1	ASPRS 1990 Class 2	Equivalent to map scale in NMAS
0.63	0.9	1.5	0.31 to 0.63	1:25	1:12.5	1:16
1.25	1.8	3.1	0.63 to 1.25	1:50	1:25	1:32
2.5	3.5	6.1	1.25 to 2.5	1:100	1:50	1:63
5.0	7.1	12.2	2.5 to 5.0	1:200	1:100	1:127
7.5	10.6	18.4	3.8 to 7.5	1:300	1:150	1:190
10.0	14.1	24.5	5.0 to 10.0	1:400	1:200	1:253
12.5	17.7	30.6	6.3 to12.5	1:500	1:250	1:317
15.0	21.2	36.7	7.5 to 15.0	1:600	1:300	1:380
17.5	24.7	42.8	8.8 to 17.5	1:700	1:350	1:444
20.0	28.3	49.0	10.0 to 20.0	1:800	1:400	1:507
22.5	31.8	55.1	11.3 to 22.5	1:900	1:450	1:570
25.0	35.4	61.2	12.5 to 25.0	1:1000	1:500	1:634
27.5	38.9	67.3	13.8 to 27.5	1:1100	1:550	1:697
30.0	42.4	73.4	15.0 to 30.0	1:1200	1:600	1:760
45.0	63.6	110.1	22.5 to 45.0	1:1800	1:900	1:1,141
60.0	84.9	146.9	30.0 to 60.0	1:2400	1:1200	1:1,521
75.0	106.1	183.6	37.5 to 75.0	1:3000	1:1500	1:1,901
100.0	141.4	244.8	50.0 to 100.0	1:4000	1:2000	1:2,535
150.0	212.1	367.2	75.0 to 150.0	1:6000	1:3000	1:3,802
200.0	282.8	489.5	100.0 to 200.0	1:8,000	1:4000	1:5,069
250.0	353.6	611.9	125.0 to 250.0	1:10,000	1:5000	1:6,337
300.0	424.3	734.3	150.0 to 300.0	1:12,000	1:6000	1:7,604
500.0	707.1	1223.9	250.0 to 500.0	1:20,000	1:10000	1:21,122
1000.0	1414.2	2447.7	500.0 to 1000.0	1:40000	1:20000	1:42,244

Table B.7 Vertical Accuracy/Quality Examples for Digital Elevation Data

Vertical Accuracy Class	Absolute Accuracy			Relative Accuracy (where applicable)		
	RMSEz Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Veg Terrain (RMSDz) (cm)	Swath-to-Swath Non-Veg Terrain (Max Diff) (cm)
1-cm	1.0	2.0	3	0.6	0.8	1.6
2.5-cm	2.5	4.9	7.5	1.5	2	4
5-cm	5.0	9.8	15	3	4	8
10-cm	10.0	19.6	30	6	8	16
15-cm	15.0	29.4	45	9	12	24
20-cm	20.0	39.2	60	12	16	32
33.3-cm	33.3	65.3	100	20	26.7	53.3
66.7-cm	66.7	130.7	200	40	53.3	106.7
100-cm	100.0	196.0	300	60	80	160
333.3-cm	333.3	653.3	1000	200	266.7	533.3

Table B.8 Vertical Accuracy of the New ASPRS 2014 Standard Compared with Legacy Standards

Vertical Accuracy Class	RMSE, Non-Vegetated (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 on Vertical Accuracy and Recommended Lidar Point Density for Digital Elevation Data According to the New ASPRS 2014 Standard

Vertical Accuracy Class	Absolute Accuracy		Recommended Minimum NPD[a] (pls/m²)	Recommended Maximum NPS[a] (m)
	RMSE, Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)		
1-cm	1.0	2.0	≥20	≤0.22
2.5-cm	2.5	4.9	16	0.25
5-cm	5.0	9.8	8	0.35
10-cm	10.0	19.6	2	0.71
15-cm	15.0	29.4	1	1.0
20-cm	20.0	39.2	0.5	1.4
33.3-cm	33.3	65.3	0.25	2.0
66.7-cm	66.7	130.7	0.1	3.2
100-cm	100.0	196.0	0.05	4.5
333.3-cm	333.3	653.3	0.01	10.0

[a] 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 pls/m²). NPS is a linear measure of the typical distance between points, and is most often expressed in meters. Although either expression can be used for any data set, NPD is usually used for lidar collections with NPS <1, and NPS is used for those with NPS ≥1. Both measures are based on all 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 $NPS = 1/\sqrt{NPD}$ and $NPD = 1/NPS^2$. 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.

B.5 CONVERTING ASPRS 2014 ACCURACY VALUES TO LEGACY ASPRS 1990 ACCURACY VALUES

In this section easy methods and examples will be provided for users who are faced with the issue of relating the standard (ASPRS 2014) to the legacy ASPRS 1990 Accuracy Standards for Large-Scale Maps. A major advantage of the new standard is it indicates accuracy based on RMSE at the ground scale. Although both the new 2014 standard and the legacy ASPRS map standard of 1990 are using the same measure of RMSE, they are different on the concept of representing the accuracy classes. The legacy ASPRS map standard of 1990 uses Class 1 for higher accuracy and Classes 2 and 3 for data with lower accuracy while the new 2014 standard refers to the map accuracy by the value of RMSE without limiting it to any class. The following examples illustrate the procedures users can follow to relate horizontal and vertical accuracies values between the new ASPRS standard of 2014 and the legacy ASPRS 1990 Accuracy Standards for Large-Scale Maps.

Example 1: Converting the Horizontal Accuracy of a Map or Orthoimagery from the New 2014 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 new 2014 standard, compute the equivalent accuracy and map scale according to the legacy ASPRS map standard of 1990, for the given map or orthoimagery.

Solution:

1. Because both standards utilize the same RMSE measure, then the accuracy of the map according to the legacy ASPRS map standard of 1990 is $RMSE_x = RMSE_y = 15$ cm
2. To find the equivalent map scale according to the legacy ASPRS map standard of 1990, 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, therefore:
   MSF = 15 (cm) × 40 = 600
   b. The map scale according to the legacy ASPRS map standard of 1990 is equal to:
      i. Scale = 1:MSF or 1:600 Class 1;
      ii. 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: Converting the Vertical Accuracy of an Elevation Dataset from the New Standard to the Legacy ASPRS Map Standard of 1990.

Given an elevation data set with a vertical accuracy of $RMSE_z = 10$ cm according to the new standard, compute the equivalent contour interval according to the legacy ASPRS map standard of 1990, for the given dataset.

Solution:
The legacy ASPRS map standard of 1990 states that:

"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."

1. Because both standards utilize the same RMSE measure to

express the vertical accuracy, then the accuracy of the elevation dataset according to the legacy ASPRS map standard of 1990 is also equal to the given $RMSE_v$ = 10 cm

2. Using the legacy ASPRS map standard of 1990 accuracy measure of $RMSE_v$ = 1/3 x contour interval (CI), the equivalent contour interval is computed according to the legacy ASPRS map standard of 1990 using the following formula:

   CI = 3 × $RMSE_v$ = 3 x 10 cm = 30 cm with Class 1,

   or CI = 15 cm with Class 2 accuracy

   However, if the user is interested in evaluating the spot height requirement according to the ASPRS 1990 standard, then the results will differ from the one obtained above. 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 a 30 cm CI, the required spot height accuracy, $RMSE_v$ = 1/6 × 30 cm = 5 cm

   Since our data is $RMSE_v$ = 10 cm, it would only support Class 2 accuracy spot elevations for this contour interval.

B.6 CONVERTING ASPRS 2014 ACCURACY VALUES TO LEGACY NMAS 1947 ACCURACY VALUES

In this section easy methods and examples will be provided for users who are faced with the issue of relating the new standard (ASPRS 2014) to the legacy National Map Accuracy Standard (NMAS) of 1947. In regard to the horizontal accuracy measure, the NMAS of 1947 states that:

"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." This is known as the Circular Map Accuracy Standard (CMAS) or Circular Error at the 90% confidence level (CE90).

Therefore, the standard uses two accuracy measures based on the map scale with the figure of "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. As for the vertical accuracy measure, the 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." This is known as 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 the new ASPRS standard of 2014 and the legacy National Map Accuracy Standard (NMAS) of 1947.

Example 3: Converting the horizontal accuracy of a map or orthoimagery from the new ASPRS 2014 standard to the legacy National Map Accuracy Standard (NMAS) of 1947.

Given a map or orthoimagery with an accuracy of $RMSE_x$ = $RMSE_y$ = 15 cm according to the new 2014 standard, compute the equivalent accuracy and map scale according to the legacy National Map Accuracy Standard (NMAS) of 1947, for the given map or orthoimagery.

Solution:

1. Because the accuracy figure of $RMSE_x$ = $RMSE_y$ = 15 cm is relatively small, it is safe to assume that such accuracy value is derived for a map with a scale larger than 1:20,000. Therefore, we can use the factor "1/30 inch."

   Use the formula CMAS (CE90) = 2.1460 × $RMSE_x$ = 2.1460 × $RMSE_y$

   CE90 = 2.1460 × 15 cm = 32.19 cm

2. Convert the CE90 to feet

   32.19 cm = 1.0561 foot

3. Use the NMAS accuracy relation of CE90 = 1/30 inch on the map, 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 = 1.0561 foot × 30 = 31.68 feet

4. The equivalent map scale according to NMAS is equal to 1" = 31.68' or 1:380

Example 4: Converting the vertical accuracy of an elevation dataset from the new ASPRS 2014 standard to the legacy National Map Accuracy Standard (NMAS) of 1947.

Given an elevation data set with a vertical accuracy of $RMSE_v$ = 10 cm according to the new ASPRS 2014 standard, compute the equivalent contour interval according to the legacy National Map Accuracy Standard (NMAS) of 1947, for the given dataset.

Solution:
As mentioned earlier, the legacy ASPRS map standard of 1990 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."

Use the following formula to compute the 90% vertical error:

1. VMAS (LE90) = 1.6449 × $RMSE_v$ = 1.6449 x 10 cm = 16.449 cm
2. Compute the contour interval (CI) using the following criteria set by the NMAS standard:

   VMAS (LE90) = 1/2 CI, or

   CI = 2 × LE90 = 2 × 16.449 cm = 32.9 cm

B.7 EXPRESSING THE ASPRS 2014 ACCURACY VALUES ACCORDING TO THE FGDC NATIONAL STANDARD FOR SPATIAL DATA ACCURACY (NSSDA)

In this section easy methods and examples will be provided for users who are faced with the issue of relating the new standard (ASPRS 2014) to the FGDC National Standard for Spatial Data Accuracy (NSSDA).

Example 5: Converting the horizontal accuracy of a map or orthoimagery from the new 2014 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 new 2014 standard, express the equivalent accuracy according to the FGDC National Standard for Spatial Data Accuracy (NSSDA), for the given map or orthoimagery.

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

Accuracy at 95% or $\text{Accuracy}_r = 2.4477 \times \text{RMSE}_x = 2.4477 \times \text{RMSE}_y$

If we assume that:

$\text{RMSE}_x = \text{RMSE}_y$ and $\text{RMSE}_r = \sqrt{\text{RMSE}_x^2 + \text{RMSE}_y^2}$, then

$\text{RMSE}_r = \sqrt{2\text{RMSE}_x^2} = \sqrt{2\text{RMSE}_y^2} = 1.4142 \times \text{RMSE}_x = 1.4142 \times \text{RMSE}_y = 1.4142 \times 15 = 21.21$ cm

also

RMSE_x or $\text{RMSE}_y = \frac{\text{RMSE}_r}{1.4142}$.

Then,

$\text{Accuracy}_r = 2.4477\left(\frac{\text{RMSE}_r}{1.4142}\right) = 1.7308(\text{RMSE}_r) = 1.7308(21.21\text{ cm}) = 36.71$ cm

Example 6: Converting the vertical accuracy of an elevation dataset from the new ASPRS 2014 standard to the FGDC National Standard for Spatial Data Accuracy (NSSDA)

Given an elevation data set with a vertical accuracy of $\text{RMSE}_z = 10$ cm according to the new ASPRS 2014 standard, express the equivalent accuracy according to the FGDC National Standard for Spatial Data Accuracy (NSSDA), for the given dataset.

Solution:
According to NSSDA, the vertical accuracy of an elevation dataset is estimated at 95% confidence level according to the following formula:

Vertical Accuracy at 95% Confidence Level = $1.9600(RMSE_z) = 1.9600(10) = 19.6$ cm

B.8 HORIZONTAL ACCURACY EXAMPLES FOR LIDAR DATA

As described in Section 7.5, the horizontal errors in lidar data are largely a function of GNSS positional error, INS angular error, and flying altitude. Therefore for a given project, if the radial horizontal positional error of the GNSS is assumed to be equal to 0.11314 m (based on 0.08 m in either X or Y), and the IMU error is 0.00427 degree in roll, pitch, and heading, the following table can be used to estimate the horizontal accuracy of lidar derived elevation data.

Table B.10 provides estimated horizontal errors, in terms of RMSE_r, in lidar elevation data as computed by the equation in section 7.5 for different flying altitudes above mean terrain.

Different lidar systems in the market have different specifications for the GNSS and IMU and therefore, the values in Table B.10 should be modified according to the equation in section 7.5.

Table B.10 Expected Horizontal Errors (RMSE_r) for Lidar Data in Terms of Flying Altitude

Altitude (m)	Positional RMSE_r (cm)	Altitude (m)	Positional RMSE_r (cm)
500	13.1	3,000	41.6
1,000	17.5	3,500	48.0
1,500	23.0	4,000	54.5
2,000	29.0	4,500	61.1
2,500	35.2	5,000	67.6

B.9 ELEVATION DATA ACCURACY VERSUS ELEVATION DATA QUALITY

In aerial photography and photogrammetry, the accuracy of the individual points in a data set is largely dependent on the scale and resolution of the source imagery. Larger scale imagery, flown at a lower altitude, produces smaller GSDs and higher measurement accuracies (both vertical and horizontal). Users have quite naturally come to equate higher density imagery (smaller GSD or smaller pixel sizes) 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, theoretically, is now limited by physical error budgets of the different components of the lidar system such as laser ranging, the GNSS, the IMU, and the encoder systems. Increasing the density of points does not change those factors. Beyond the physical error budget limitations, all data must also be properly controlled, calibrated, boresighted, and processed. Errors introduced during any of these steps will affect the accuracy of the data, regardless of 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.

In order to accurately represent a complex surface, denser data are necessary to capture the surface details for accurate mapping of small linear features such as curbs and micro drainage features, for example. The use of denser data for complex surface representation does not make the individual lidar measurements any more accurate, but does improve the accuracy of the derived surface at locations between the lidar measurements (as each reach between points is shorter).

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 in less interpolation between points and improved surface definition because more characteristics of the actual ground surface are being measured, not interpolated. The use of more ground points is more critical in variable or complex surfaces, such as mountainous terrain, where generalized interpolation between points would not accurately model all of the changes in the surface.

Increased density may not improve the accuracy in flat, open terrain where interpolation between points would still adequately represent the ground surface. However, in areas where denser data may not be necessary to improve the vertical accuracy of data, a higher density data set 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. When lidar intensity is to be used in product derivation or algorithms, high collection density is always useful.

ANNEX C - ACCURACY TESTING AND REPORTING GUIDELINES (NORMATIVE)

When errors are normally distributed, accuracy testing can be performed with RMSE values, standard deviations, mean errors, maximum and minimum errors, and unit-less skew and kurtosis values. When errors are not normally distributed, alternative methods must be used. If the number of test points (checkpoints) is sufficient, testing and reporting can be performed using 95th percentile errors. A percentile rank is the percentage of errors that fall at or below a given value. Errors are visualized with histograms that show the pattern of errors relative to a normal error distribution.

The ability of RMSE, 95th percentile, or any other statistic to estimate accuracy at the 95% confidence level is largely dependent on the number and accuracy of the checkpoints used to test the accuracy of a data set being evaluated. Whereas 100 or more is a desirable number of checkpoints, that number of checkpoints may be impractical and unaffordable for many projects, especially small project areas.

C.1 CHECKPOINT REQUIREMENTS

Both the total number of points and spatial distribution of checkpoints play an important role in the accuracy evaluation of any geospatial data. Prior guidelines and accuracy standards typically specify the required number of checkpoints and, in some cases, the land-cover types, but defining and/or characterizing the spatial distribution of the points was not required. While characterizing the point distribution is not a simple process and no practical method is available at this time, characterizing the point distribution by some measure and, consequently, providing a quality number is undoubtedly both realistic and necessary. ASPRS encourages research into this topic, peer reviewed, and published in *Photogrammetric Engineering & Remote Sensing* for public testing and comment.

Until a quantitative characterization and specification of the spatial distribution of checkpoints across a project is developed, more general methods of determining an appropriate checkpoint distribution must be implemented. In the interim, this Annex provides general recommendations and guidelines related to the number of checkpoints, distribution across land cover types, and spatial distribution.

C.2 NUMBER OF CHECKPOINTS REQUIRED

Table C.1 lists ASPRS recommendations for the number of checkpoints to be used for vertical and horizontal accuracy testing of elevation data sets and for horizontal accuracy testing of digital orthoimagery and planimetric data sets.

Using metric units, ASPRS recommends 100 static vertical checkpoints for the first 2,500 square kilometer area within the project, which provides a statistically defensible number of samples on which to base a valid vertical accuracy assessment.

For horizontal testing of areas >2500 km², 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 >2,500 km², add five additional vertical checkpoints for each additional 500 km² area. Each additional set of five vertical checkpoints for 500 km² would include three checkpoints for NVA and two for 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.3 DISTRIBUTION OF VERTICAL CHECKPOINTS ACROSS LAND COVER TYPES

In contrast to the recommendations in Table C.1, both the 2003 and the current FEMA guidelines reference the five general land cover types, and specify a minimum of 20 checkpoints in each of three to five land cover categories as they exist within the project area, for a total of 60 to 100 checkpoints. Under the current FEMA guidelines, this quantity applies to each 5,180 square kilometer (2000 square mile) area, or partial area, within the project.

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.

Table C.1 Recommended Number of Checkpoints Based on Area

Project Area (Square Kilometers)	Horizontal Accuracy Testing of Orthoimagery and Planimetrics	Vertical and Horizontal Accuracy Testing of Elevation Data sets		
	Total Number of Static 2D/3D Checkpoints (clearly-defined points)	Number of Static 3D Checkpoints in NVA*	Number of Static 3D Checkpoints in VVA	Total Number of Static 3D Checkpoints
≤500	20	20	5	25
501-750	25	20	10	30
751-1000	30	25	15	40
1001-1250	35	30	20	50
1251-1500	40	35	25	60
1501-1750	45	40	30	70
1751-2000	50	45	35	80
2001-2250	55	50	40	90
2251-2500	60	55	45	100

*Although vertical check points are normally not well defined, where feasible, the horizontal accuracy of lidar data sets should be tested by surveying approximately half of all NVA check points at the ends of paint stripes or other point features that are visible and can be measured on lidar intensity returns.

C.4 NSSDA METHODOLOGY FOR CHECKPOINT DISTRIBUTION (HORIZONTAL AND VERTICAL TESTING)

The NSSDA offers a method that can be applied to projects that are generally rectangular in shape and are largely non-vegetated. These methods do not apply to the irregular shapes of many projects or to most vegetated land cover types. The NSSDA 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. (FGDC, 1998)"[10]

ASPRS recommends that, where appropriate and to the highest degree possible, the NSSDA method be applied to the project and incorporated land cover type areas. 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.

Clearly, 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.5 VERTICAL CHECKPOINT ACCURACY

Vertical checkpoints need not be clearly-defined point features. Kinematic checkpoints (surveyed from a moving platform), which are less accurate than static checkpoints, can be used in any quantity as supplemental data, but the core accuracy assessment must be based on static surveys, consistent with NOAA Technical Memorandum NOS NGS-58, *Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm)*, or equivalent. NGS-58 establishes ellipsoid height accuracies of 5 cm at the 95% confidence level for network accuracies relative to the geodetic network, as well as ellipsoid height accuracies of 2 cm and 5 cm at the 95% confidence level for accuracies relative to local control.

As with horizontal accuracy testing, vertical checkpoints should be three times more accurate than the required accuracy of the elevation data set being tested.

C.6 TESTING AND REPORTING OF HORIZONTAL ACCURACIES

When errors are normally distributed and the mean is small, ASPRS endorses the NSSDA procedures for testing and reporting the horizontal accuracy of digital geospatial data. The NSSDA methodology applies to most digital orthoimagery and planimetric data sets where systematic errors and bias have been appropriately removed. Accuracy statistics and examples are outlined in more detail in Annex D.

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.

For horizontal accuracy testing of lidar data sets, 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.

The specific testing methodology used should be identified in the metadata.

C.7 TESTING AND REPORTING OF VERTICAL ACCURACIES

For testing and reporting the vertical accuracy of digital elevation data, ASPRS endorses the *NDEP Guidelines for Digital Elevation Data*, with slight modifications from FVA, SVA, and CVA procedures. This ASPRS standard reports the Non-vegetated Vertical Accuracy (NVA) at the 95% confidence level in all non-vegetated land cover categories combined and reports the Vegetated Vertical Accuracy (VVA) at the 95th percentile in all vegetated land cover categories combined.

If the vertical errors are normally distributed, the sample size sufficiently large, and the mean error is sufficiently small, ASPRS endorses NSSDA and NDEP methodologies for approximating vertical accuracies at the 95% confidence level, which applies to NVA checkpoints in all open terrain (bare soil, sand, rocks, and short grass) as well as urban terrain (asphalt and concrete surfaces) land cover categories.

In contrast, VVA is computed by using the 95th percentile of the absolute value of all elevation errors in all vegetated land cover categories combined, to include tall weeds and crops, brush lands, and lightly-to fully-forested land cover categories. By testing and reporting the VVA separate from the NVA, ASPRS draws a clear distinction between non-vegetated terrain where errors typically follow a normal

[10] Federal Geographic Data Committee. (1998). FGDC-STD-007.3-1998, Geospatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy, FGDC, c/o U.S. Geological Survey, www.fgdc.fgdc.gov/standards/documents/standards/accuracy/chapter3

distribution suitable for RMSE statistical analyses, and vegetated terrain where errors do not necessarily follow a normal distribution and where the 95th percentile value more fairly estimates vertical accuracy at a 95% confidence level.

C.8 LOW CONFIDENCE AREAS

For stereo-compiled elevation data sets, photogrammetrists should capture two-dimensional closed polygons for "low confidence areas" where the bare-earth DTM may not meet the overall data accuracy requirements. Because photogrammetrists cannot see the ground in stereo beneath dense vegetation, in deep shadows or where the imagery is otherwise obscured, reliable data cannot be collected in those areas. Traditionally, contours within these obscured areas would be published as dashed contour lines. A compiler should make the determination as to whether the data being digitized is within NVA and VVA accuracies or not; 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. Although costs will be slightly higher, ASPRS recommends that "low confidence areas" for lidar be required and delivered as two-dimensional (2D) polygons based on the following four criteria:

1. Nominal ground point density (NGPD);
2. Cell size for the raster analysis;
3. Search radius to determine average ground point densities; and
4. Minimum size area appropriate to aggregate ground point densities and show a generalized low confidence area (minimum mapping unit).

This approach describes a raster-based analysis where the raster cell size is equal to the Search Radius listed for each Vertical Data Accuracy Class. Raster results are to be converted into polygons for delivery.

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 lists the values for the above low confidence area criteria that apply to each vertical accuracy class.

Low confidence criteria and the values in Table C.2 are based on the following assumptions:

- **Ground Point Density**: Areas with ground point densities less than or equal to ¼ of the recommended nominal pulse density (pulse per square meter) or twice the nominal pulse spacing are candidates for Low Confidence Areas. For example: a specification requires an NPS of 1 meter (or an NPD of 1 ppsm) but the elevation data in some areas resulted in a nominal ground point density of 0.25 point per square meter (nominal ground point spacing of 2 meters). Such areas are good candidate for "low confidence" areas.
- **Raster Analysis Cell Size**: Because the analysis of ground point density will most likely be raster based, the cell size at which the analysis will be performed needs to be specified. The recommendation is that the cell size equals the search radius.
- **Search Radius for Computing Point Densities**: Because point data are being assessed, an area must be specified in order to compute the average point density within this area. The standards recommend a search area with a radius equal to 3 * NPS (*not the Low Confidence NGPS*). This distance 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.
- **Minimum Size for Low Confidence Polygons**: The areas computed with low densities should be aggregated together. Unless specifically requested by clients, structures/buildings and water should be removed from the aggregated low density polygons as these features are not true Low Confidence.

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 define Low Confidence Area polygons. These determinations should be a function of the topography, land cover, and final use of the maps.

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 could be applied to the Low Confidence Polygons, if desired.

TABLE C.2 LOW CONFIDENCE AREAS

Vertical Accuracy Class	Recommended Project Min NPD (pts/m²) (Max NPS (m))	Recommended Low Confidence Min NGPD (pts/m²) (Max NGPS (m))	Search Radius and Cell Size for Computing NGPD (m)	Low Confidence Polygons Min Area (acres (m²))
1-cm	20 (0.22)	5 (0.45)	0.67	0.5 (2,000)
2.5-cm	16 (0.25)	4 (0.50)	0.75	1 (4,000)
5-cm	8 (0.35)	2 (0.71)	1.06	2 (8,000)
10-cm	2 (0.71)	0.5 (1.41)	2.12	5 (20,000)
15-cm	1 (1.0)	0.25 (2.0)	3.00	5 (20,000)
20-cm	0.5 (1.4)	0.125 (2.8)	4.24	5 (20,000)
33.3-cm	0.25 (2.0)	0.0625 (4.0)	6.0	10 (40,000)
66.7-cm	0.1 (3.2)	0.025 (6.3)	9.5	15 (60,000)
100-cm	0.05 (4.5)	0.0125 (8.9)	13.4	20 (80,000)
333.3-cm	0.01 (10.0)	0.0025 (20.0)	30.0	25 (100,000)

There are two distinctly different types of low confidence areas:

- The first types of low confidence areas are identified by the data producer - *in advance* - where passable identification of the bare earth is expected to be unlikely or impossible. These are areas where no control or checkpoints should be located and where contours, if produced, should be dashed. They are exempt from accuracy assessment. Mangroves, swamps, and inundated wetland marshes are prime candidates for such advance delineation.
- The second types of low confidence areas are valid VVA areas, normally forests that should also 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 notably reduced density of bare-earth points.

Providing Low Confidence Area polygons allows lidar data providers to protect themselves from unusable/unfair checkpoints in swamps and protects 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.9 ERRONEOUS CHECKPOINTS

Occasionally, a checkpoint may be erroneous or inappropriate for use at no fault of the lidar survey. Such a point may be removed from the accuracy assessment calculation:

- if it is demonstrated, with pictures and descriptions, that the checkpoint was improperly located, such as when a vertical checkpoint is on steep terrain or within a few meters of a significant breakline that redefines the slope of the area being 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; or
- 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 (>3 *s) is NOT a defensible explanation.

C.10 RELATIVE ACCURACY COMPARISON POINT LOCATION AND CRITERIA FOR LIDAR SWATH-TO-SWATH ACCURACY ASSESSMENT

To the greatest degree possible, relative accuracy testing locations should meet the following criteria:

1. include all overlap areas (sidelap, endlap, and crossflights);
2. be evenly distributed throughout the full width and length of each overlap area;
3. be located in non-vegetated areas (clear and open terrain and urban areas);
4. be at least 3 meters away from any vertical artifact or abrupt change in elevation;
5. be on uniform slopes; and,
6. be within the geometrically reliable portion of both swaths (excluding the extreme edge points of the swaths). For lidar sensors with zigzag scanning patterns from oscillating mirrors, the geometrically reliable portion excludes about 5% (2.5 % on either side); lidar sensors with circular or elliptical scanning patterns are generally reliable throughout.

While the $RMSD_z$ value may be calculated from a set of specific test location points, the Maximum Difference requirement is not limited to these locations; it applies to all locations within the entire data set that meet the above criteria.

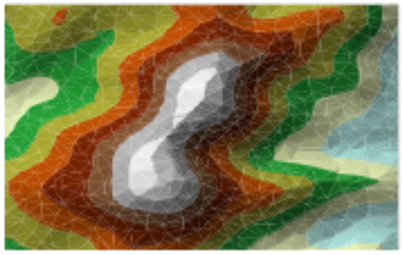
C.11 INTERPOLATION OF ELEVATION REPRESENTED SURFACE FOR CHECKPOINT COMPARISONS

The represented surface of an elevation data set is normally a TIN (Plate C.1) or a raster DEM (Plate C.1).

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 commonly represented by a TIN or raster DEM.

Vertical accuracy of point-based elevation datasets should be tested by creating a TIN from the point based elevation dataset and comparing the TIN elevations to the checkpoint elevations. TINs should be used to test the vertical accuracy of point based elevation datasets because it is unlikely a checkpoint will be located at the location of a discrete elevation point. The TIN methodology is the most commonly used method 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 tested by comparing the elevation of the DEM, which is already a continuous surface, to the checkpoint elevations. For most DEM datasets, it is recommended that the elevation of the DEM is determined by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint. However, in some instances, such as when the DEM being tested is at a lower resolution typical of global datasets or when the truth data has an area footprint associated with it rather than a single x/y coordinate, it may be better to use interpolation methods to determine the elevation of the DEM dataset. Vendors should seek approval from clients if methods other than extraction are to be used to determine elevation values of the DEM dataset. Vertical accuracy testing methods listed in metadata and reports should state if elevation values were extracted from the tested dataset at the x/y 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 dataset. If further interpolation was used, the interpolation method and full process used should be detailed accordingly.



Represented as a TIN

Represented as a Raster DEM

Plate C.1. Topographic Surface

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 $RMSE_x$, $RMSE_y$, $RMSE_z$ and $RMSE_r$, 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.

Example on the NSSDA Accuracy Computations:

For the purposes of demonstration, suppose you have five checkpoints to verify the final horizontal and vertical accuracy for a data set (normally a minimum of 20 points would be needed). 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 necessary statistics. In this abbreviated example, the data are intended to meet a horizontal accuracy class with a maximum $RMSE_x$ and $RMSE_y$ of 15 cm and the 10 cm vertical accuracy class.

Computation of Mean Errors in x/y/z:

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

where:

x_i is the ith 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:

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

Mean error in Northing:

$$\bar{y} = \frac{-0.070 - 0.100 - 0.070 + 0.150 + 0.120}{5} = 0.006\,\text{m}$$

Mean error in Elevation:

$$\bar{z} = \frac{-0.070 + 0.010 + 0.102 - 0.100 + 0.087}{5} = 0.006\,\text{m}$$

Table D.1 NSSDA Accuracy Statistics for Example Data set with 3D Coordinates

Point ID	Map-derived values			Survey Check Point Values			Residuals (Errors)		
	Easting (E)	Northing (N)	Elevation (H)	Easting (E)	Northing (N)	Elevation (H)	Δx Easting (E)	Δy Northing (N)	Δz Elevation (H)
	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	395893.089	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	0.006
RMSE (m)							0.102	0.106	0.081
RMSEr (m)							0.147	=SQRT($RMSE_x^2 + RMSE_y^2$)	
NSSDA Horizontal Accuracy, (ACCr) at 95% Confidence Level							0.255	=RMSEr × 1.7308	
NSSDA Vertical Accuracy, (ACCz) at 95% Confidence Level							0.160	=RMSEz × 1.9600	

Computation of Sample Standard Deviation:

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

where:

x_i is the ith error in the specified direction,

$\bar{x}$ 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:

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

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 Squares Error:

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

where:

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

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

n is the number of checkpoints tested,

i is an integer ranging from 1 to n.

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

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

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

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

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 =

$$2.4477\left(\frac{RMSE_r}{1.4142}\right) = 1.7308\left(RMSE_r\right) = 1.7308\left(0.148\right) = \mathbf{0.255\,m}$$

Vertical Accuracy at 95% Confidence Level =

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

$$\sqrt{\left(\left(0.102^2\right)+\left(0.107^2\right)\right)} = 0.148\text{m}$$

D.2 COMPARISON WITH NDEP VERTICAL ACCURACY STATISTICS

Whereas the NSSDA assumes that systematic errors have been eliminated as best as possible and that all remaining errors are random errors that follow a normal distribution, the ASPRS standard recognizes that elevation errors, especially in dense vegetation, do not necessarily follow a normal error distribution, as demonstrated by the error histogram of 100 checkpoints at Figure D.1 used as an example elevation data set for this Annex.

In vegetated land cover categories, the ASPRS standard (based on NDEP vertical accuracy statistics) uses the 95th percentile errors because a single outlier, when squared in the RMSE calculation, will unfairly distort the tested vertical accuracy statistic at the 95% confidence level. Unless errors can be found in the surveyed checkpoint, or the location of the checkpoint does not comply with ASPRS guidelines for location of vertical checkpoints, such outliers should not be discarded. Instead, such outliers should be included in the calculation of the 95th percentile because: (a) the outliers help identify legitimate issues in mapping the bare-earth terrain in dense vegetation, and (b) the 95th percentile, by definition, identifies that 95% of errors in the data set have errors with respect to true ground elevation that are equal to or smaller than the 95th percentile - the goal of the NSSDA.

Example Elevation Data set

Figure D.1, plus Tables D.2 and D.3, refer to an actual elevation data set tested by prior methods compared to the current ASPRS standard.

Plate D.1 shows an actual error histogram resulting from 100 checkpoints, 20 each in five land cover categories: (1) open terrain, (2) urban terrain, concrete and asphalt, (3) tall weeds and crops, (4) brush lands and trees, and (5) fully forested. In this lidar example, the smaller outlier of 49 cm is in tall weeds and crops, and the larger outlier of 70 cm is in the fully forested land cover category. The remaining 98 elevation error values appear to approximate a normal error distribution with a mean error close to zero; therefore, the sample standard deviation and RMSE values are nearly identical. When mean errors are not close to zero, the sample standard deviation values will normally be smaller than the RMSE values.

Without considering the 95th percentile errors, traditional accuracy statistics, which preceded these *ASPRS Positional Accuracy Standards for Digital Geospatial Data*, would be as shown in Table D.2. Note that the maximum error, skewness (γ_1), kurtosis (γ_2), standard deviation and $RMSE_z$ values are somewhat higher for weeds and crops because of the 49 cm outlier, and they are much higher for the fully forested land cover category because of the 70 cm outlier.

The ASPRS standards listed in Table 7.5 define two new terms: Non-vegetated Vertical Accuracy (NVA) based on RMSE$_z$ statistics and Vegetated Vertical Accuracy (VVA) based on 95th percentile statistics. The NVA consolidates the NDEP's non-vegetated land cover categories (open terrain and urban terrain, in this example), whereas the VVA consolidates the NDEP's vegetated land cover categories (weeds and crops, brush lands, and fully forested, in this example). Table D.3 shows ASPRS statistics and reporting methods compared to both NSSDA and NDEP.

D.3 COMPUTATION OF PERCENTILE

There are different approaches to determining percentile ranks and associated values. This standard recommends the use of the following equations for computing percentile rank and percentile as the most appropriate for estimating the Vegetated Vertical Accuracy.

Note that 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.

Table D.2 Traditional Error Statistics for Example Elevation Data set

Land Cover Category	# of Checkpoints	Min (m)	Max (m)	Mean (m)	Mean Absolute (m)	Median (m)	γ_1	γ_2	s (m)	RMSE$_z$ (m)
Open Terrain	20	–0.10	0.08	–0.02	0.04	0.00	–0.19	–0.64	0.05	0.05
Urban Terrain	20	–0.15	0.11	0.01	0.06	0.02	–0.84	0.22	0.07	0.07
Weeds & Crops	20	–0.13	0.49	0.02	0.08	–0.01	2.68	9.43	0.13	0.13
Brush Lands	20	–0.10	0.17	0.04	0.06	0.04	–0.18	–0.31	0.07	0.08
Fully Forested	20	–0.13	0.70	0.03	0.10	0.00	3.08	11.46	0.18	0.17
Consolidated	100	–0.15	0.70	0.02	0.07	0.01	3.18	17.12	0.11	0.11

Table D.3 Comparison of NSSDA, NDEP, and ASPRS Statistics for Example Elevation Data Set

Land Cover Category	NSSDA Accuracyz at 95% confidence level based on RMSE$_z$ * 1.9600 (m)	NDEP FVA, plus SVAs and CVA based on the 95th Percentile (m)	NDEP Accuracy Term	ASPRS Vertical Accuracy (m)	ASPRS Accuracy Term
Open Terrain	0.10	0.10	FVA	0.12	NVA
Urban Terrain	0.14	0.13	SVA		
Weeds & Crops	0.25	0.15	SVA	0.167	VVA
Brush Lands	0.16	0.14	SVA		
Fully Forested	0.33	0.21	SVA		
Consolidated	0.22	0.13	CVA	N/A	N/A

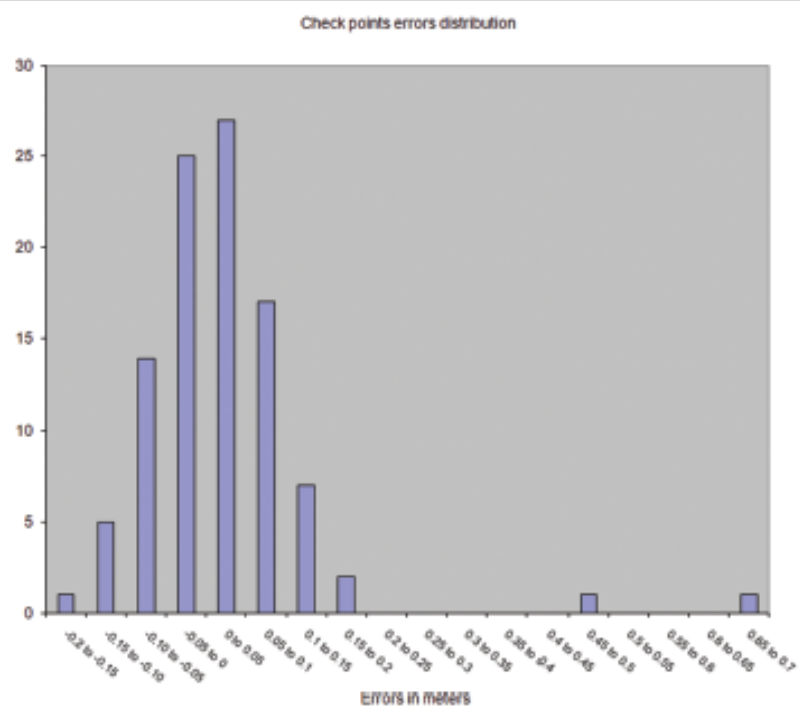


Plate D.1 Error Histogram of Typical Elevation Data Set, Showing Two Outliers in Vegetated Areas.

The percentile rank (n) is first calculated for the desired percentile using the following equation:

$$n = \left(\left(\left(\frac{P}{100}\right) * (N-1)\right) + 1\right)$$

where: n is the rank of the observation that contains the Pth percentile, P is the proportion (of 100) at which the percentile is desired (e.g., 95 for 95th percentile), and N is the number of observations in the sample data set.

Once the rank of the observation is determined, the percentile (Q_p) can then be interpolated from the upper and lower observations using the following equation:

$$Q_p = \left(A[n_w] + \left(n_d * \left(A[n_w + 1] - A[n_w]\right)\right)\right)$$

where: Q_p is the Pth percentile; the value at rank n, A is an array of the absolute values of the samples, indexed in ascending order from 1 to N, $A[i]$ is the sample value of array A at index i (e.g., n_w or n_d) - i must be an integer between 1 and N - n is the rank of the observation that contains the Pth percentile, n_w is the whole number component of n (e.g., 3 of 3.14), and n_d is the decimal component of n (e.g., 0.14 of 3.14).

Example:

Given a sample data set $\{X_1, X_2 \ldots X_N\}$ =

$\{7, -33, -9, 5, -16, 22, 36, 37, 39, -11, 45, 28, 45, 19, -46, 10, 48, 44, 51, -27\}$

$(N = 20)$,

calculate the 95th percentile $(P = 95)$:

Step 1: Take the absolute value of each observation:

$\{7, 33, 9, 5, 16, 22, 36, 37, 39, 11, 45, 28, 45, 19, 46, 10, 48, 44, 51, 27\}$

Step 2: Sort the absolute values in ascending order:

$A = \{5, 7, 9, 10, 11, 16, 19, 22, 27, 28, 33, 36, 37, 39, 44, 45, 45, 46, 48, 51\}$

Step 3: Compute the percentile rank n for P=95:

$$n = \left(\left(\left(\frac{P}{100}\right) * (N-1)\right) + 1\right) = \left(\left(\left(\frac{95}{100}\right) * (20-1)\right) + 1\right) = 19.05$$

The 95th percentile rank (n) of the sample data set is 19.05

Step 4: Compute the percentile value Q_p by interpolating between observations 19 and 20:

$$Q_p = \left(A[n_w] + \left(n_d * \left(A[n_w + 1] - A[n_w]\right)\right)\right) = \left(48 + \left(0.05 * (51 - 48)\right)\right) = 48.15$$

The 95th percentile (Q_p) of the sample data set is 48.15.