The Center for Photogrammetric Training

10 MAPPING ACCURACY STANDARDS

INTRODUCTION

Many different mapping standards exist at all levels within the U.S. Sometimes, it is the client who will dictate the accuracy of the map. In other instances, the client will refer to published standards such as the National Map Accuracy Standards and use those in evaluating the work of the mapping professional. Several state agencies have developed their own special standards that not only guide them in their work but also use them to ensure that the photogrammetrist has met the criteria that agency has established. Finally, many professional organizations have also promulgated standards that define minimum criteria whereby professional conduct can be measured.

Accuracy guidelines are generally broken down into two general categories: planimetric accuracy and height accuracy. The accuracy of planimetry is directly proportional to the scale of the photograph. Height accuracy is proportional to the flying height or to the square of the object distance.

ACCURACY OF PHOTOGRAMMETRY

Before one begins to look at mapping standards one must understand the accuracy potential of the tools used in the mapping. Quite clearly, accuracy of stereoplotters will vary between instruments. For example, analytical plotters have an accuracy of ± 1-4 μm at the photo scale. Accuracy of photogrammetric measurements will also depend on the points upon which the measurements are being made.

For targeted points, a good estimate of the accuracy in measuring the point would be $\sigma_{x,y} = \pm 6\ \mu m$. in the photo plane. For elevation, the accuracy will be dependent on the camera. Thus we have:

$\sigma_Z = \pm 0.06‰$ of the flying height[1] for normal and wide angle lenses
$\sigma_Z = \pm 0.08‰$ of the flying height for super-wide angle lenses

[1] ‰ is referred to as per-percent. Percent is a hundredth while per-percent is a thousandth. Then, $0.1\% = 1‰$.

These error estimates account for all of the error influences and they can be improved up to 50% if additional calculations are undertaken to remove known errors within the measurement.

Let's look at an example. Assume that photography is acquired at a scale of 1" = 500' (1:6,000) with a wide-angle camera having a nominal focal length of 150 mm. An analytical plotter is used to make the photo measurements. What is the planimetric and height error that one can expect?

Solution: For planimetry, the accuracy is (knowing that 6 μm = 0.0006 cm):

$$\sigma_{X,Y} = (6{,}000)(0.0006 \text{ cm}) = \pm 3.6 \text{ cm}$$

For the height accuracy, the flying height is found using the scale relationship $S = f/H' \Rightarrow H' = f/S$ or the flying height above ground is the product of the focal length times the denominator of the scale. Recognizing that 150 mm = 15 cm, the accuracy of the height measurement is

$$\sigma_Z = (6{,}000)(15 \text{ cm})(0.00006) = \pm 5.4 \text{ cm}$$

Artificial targets present a unique and well-defined point within the image from which accurate measurements can be made. But, they are used only for control purposes. Thus, the photogrammetrist is required to measure photo identifiable features like corners of building, streets, manholes, etc. To investigate the accuracy of measuring these types of points, one must consider the uncertainty in the definition of the feature. Thus, accuracy estimates can be shown to be

$$\sigma_{X,Y_{Nat}} = \sqrt{\sigma^2_{X,Y_{Tar}} + \sigma^2_{X,Y_{Feat}}}$$

$$\sigma_{Z_{Nat}} = \sqrt{\sigma^2_{Z_{Tar}} + \sigma^2_{Z_{Feat}}}$$

where the subscript "Nat" refers to the natural point, the subscript "Tar" relates to the uncertainty one could expect from a targeted point, and the subscript "Feat" relates to the uncertainty in the feature definition.

Some example uncertainties that one can expect from definition of the natural point are shown in table 1.

Type of Point	$\sigma_{X,Y_{Feat}}$	$\sigma_{Z_{Feat}}$
House and Fence Corner	7 - 12 cm	8 - 15 cm
Manhole Cover	4 - 6 cm	1 - 3 cm
Field Corner	20 - 100 cm	10 - 20 cm
Bushes and Trees	20 - 100 cm	20 - 100 cm

Table 1. Example uncertainties from natural points

Example: Using the values from the previous example, what is the uncertainty for the measurement of a house corner and a field corner?

Solution: Given that the uncertainties are given in terms of range, let's use the average of the values. Thus, for the house corner $\sigma_{X,Y_{Feat}} = \pm 9.5\ \text{cm}$ and $\sigma_{Z_{Feat}} = \pm 11.5\ \text{cm}$ while for the field corner $\sigma_{X,Y_{Feat}} = \pm 60\ \text{cm}$ and $\sigma_{Z_{Feat}} = \pm 15\ \text{cm}$. Then the uncertainties are found as:

$$\sigma_{X,Y_{House}} = \sqrt{(3.6\,\text{cm})^2 + (9.5\ \text{cm})^2} = \pm 10\ \text{cm}$$

$$\sigma_{Z_{House}} = \sqrt{(5.4\,\text{cm})^2 + (11.5\ \text{cm})^2} = \pm 13\ \text{cm}$$

$$\sigma_{X,Y_{Field}} = \sqrt{(3.6\,\text{cm})^2 + (60\ \text{cm})^2} = \pm 60\ \text{cm}$$

$$\sigma_{Z_{Field}} = \sqrt{(5.4\,\text{cm})^2 + (15\ \text{cm})^2} = \pm 16\ \text{cm}$$

Some natural points exhibit very similar characteristics as artificial targets. In other words, the definition of the point is well-defined because of the geometry of the feature and contrast on the film. For example, a concrete sidewalk with grass around it will provide good contrast between the features. Therefore, careful selection of these photo identifiable points could yield almost the same accuracy as an artificial target.

When measuring features in the stereomodel, the normal practice is to measure points along the feature. For example, when mapping a house, normally the house corners are measured and then lines are drawn between the points to form the shape. If one were to physically measure the line by tracing it using the floating mark, accuracy is significantly reduced. From empirical tests, the uncertainty, σ_G, of a planimetric line in the photo is

$\sigma_G = \pm 45\,\mu m$. Using handwheels with a low gear ratio can improve these results significantly.

Drawing contour lines can be done directly by tracing them in the stereomodel using the floating mark. As a general rule, measuring contours directly is more accurate than measuring terrain points for a digital terrain model/digital elevation model (DTM/DEM) and having the software generate the contours. This may appear to be a dichotomy on the surface since measuring the ground elevation at a point is more accurate than a point on a contour line. The reason for this is that the software uses a mathematical model to generate the contours and this contains uncertainty as well. The downside of measuring contours directly is that it requires a highly skilled plotter operator. This is a very specialized skill that not everyone can obtain because the operator must have excellent stereoscopic visual capabilities and eye-hand coordination. It is also a labor intensive task that adds cost to a project.

The accuracy of direct measurement of a contour line is shown using the Koppe formula, which expresses this error in terms of the slope of the terrain. This is shown as

$$\sigma_H = \sigma_Z + \sigma_G \tan\alpha$$

where: $\sigma_Z =$ the accuracy of the height measurements within a stereomodel assuming 60% overlap. Again, this value will be different for different cameras. Hence,

$\sigma_Z = \pm 0.2\,‰\,h$ for normal and wide angle lenses

$\sigma_Z = \pm 0.25\,‰\,h$ for super-wide angle lenses.

Here h is the projection distance within the stereoplotter.

$\sigma_G =$ the planimetric accuracy of the contour line. Since planimetric accuracy is a function of the map scale, it will have the following values:

$\sigma_G = \pm 100\,\mu m$ in the photo for large scale maps

$\sigma_G = \pm 0.2\,mm$ in the photo for small scale maps

$\alpha =$ slope of the terrain.

The reason why σ_G is larger than the values given previously is because it is not a defined line that one can see within the stereomodel. The operator will set the z-wheel to the desired elevation and then search the model to find where that line exists.

Generally, the second term in the Koppe formula is neglected, except for steep terrain. Therefore, the uncertainty in direct plotting is often given as

$$\sigma_H = \pm 0.25 \text{‰}\, h$$

FEDERAL STANDARDS

National Map Accuracy Standards

One of the most widely quoted standards is the National Map Accuracy Standards (NMAS) that have been developed by the federal government. In terms of positional tolerances, they establish minimum criteria at the 90% level for both planimetry and elevations. For planimetry, maps at a scale larger than 1:20,000 can have no more than 10% of the points tested in error, at the map publication scale, by more than 1/30 inch. For maps at a scale of 1:20,000 or smaller, the minimum is 1/50 inch. For elevations at all publication scales, no more than 10% of the elevations tested shall be in error by more than 1/2 the contour interval. The reason scale is not specified in the NMAS for vertical accuracy is because the scale of the map is a limiting factor in depicting contours. As the map scale gets smaller and smaller the contour interval becomes larger and larger until, at some point, plotting contours is not technically or aesthetically practical.

The NMAS refers to well-defined points. As it pertains to this standard, a well-defined point is one that is easily recoverable or visible on the ground. Thus, a well-defined point would be much different using conventional field surveying than using aerial photography. While a monument may be easily recovered in the field, it may not be visible on the aerial photo. Moreover, when it comes to imagery, scale will also be a major factor. A road intersection on a small scale image may be well defined but at a large scale, it will be very difficult to ascertain where the centers of the road actually intersect.

One of the important aspects of the National Map Accuracy Standards is where the compliance is measured. Here they specify that accuracy will be tested at the map scale. Survey data of a higher accuracy than the map will be scaled to the map and then directly compared to the mapped data.

These standards have been unchanged for fifty years (published initially on June 10, 1941, and last revised on June 17, 1947) and many in the mapping community have called for their revision. The complete National Map Accuracy Standards are given as:

> *With a view to the utmost economy and expedition in producing maps which fulfill not only the broad needs for standard or principal maps, but also the reasonable particular needs of individual agencies, standards of accuracy for published maps are defined as follows:*
>
> 1. *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. These limits of accuracy will apply in all cases to positions of well-defined points only. "Well-defined" points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general what is "well-defined" will also be determined by what is "plottable" on the scale of the map within 1/100 inch. Thus while the intersection of two road or property lines meeting at right angles, would come within a sensible interpretation, identification of the intersection of such lines meeting at right angles, would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc., etc.*
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> 2. *Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of all elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.*
>
> 3. *The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy. Tests shall be made by the producing agency, which shall also determine which of its maps are to be tested, and the extent of such testing.*

4. *Published maps meeting these accuracy requirements shall note this fact in their legends, as follows: This map complies with the national standard map accuracy requirements."*[2]

5. *Published maps whose errors exceed those aforestated shall omit from their legends all mention of standard accuracy.*

6. *When a published map is a considerable enlargement of a map drawing ("manuscript") or of a published map, that fact shall be stated in the legend. For example, "This map is an enlargement of a 1:20,000-scale map drawing," or "This map is an enlargement of a 1:24,000-scale published map."*

7. *To facilitate ready interchange and use of basic information for map construction among all Federal mapmaking agencies, manuscript maps are published maps, wherever economically feasible and consistent with the uses to which the map is to be put, shall conform to latitude and longitude boundaries, being 15 minutes of latitude and longitude, of 7-1/2 minutes, or 3-3/4 minutes in size.*

National Standard for Spatial Data Accuracy

The National Standard for Spatial Data Accuracy (NSSDA) represents the most recent mapping standard adopted by the Federal Government. Like some of the standards that will be discussed later, most notably the American Society for Photogrammetry and Remote Sensing (ASPRS) Standards for Large-Scale Maps and the Engineering Map Accuracy Standards, the NSSDA utilizes a statistical approach to determine the positional accuracy of mapped points. In fact, all of these standards are related.

The NSSDA differs from the NMAS in that no threshold is specified. It is up to the contracting agency as to what the minimum criteria should be. These values could be derived from the NMAS or ASPRS standards, or completely different minimum criteria can be developed.

Like other mapping standards, the National Standard for Spatial Data Accuracy compares the mapped position with the corresponding position of the same point from a survey of higher accuracy. From these differences, a root mean square (rms) error is determined. This is found for each coordinate value [FGDC, 1998]. The rms errors are shown as:

[2] Wording of accuracy compliance statement reads "This map complies with national map accuracy standards" in revision of June 17, 1947.

$$rms_X = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{Map_i} - X_{Survey_i}\right)^2}{n}}$$

$$rms_Y = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{Map_i} - Y_{Survey_i}\right)^2}{n}}$$

$$rms_Z = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{Map_i} - Z_{Survey_i}\right)^2}{n}}$$

where the subscript "Map" indicates the appropriate mapped position of the check point, the subscript "Survey" is the corresponding value obtained from a survey of higher order, and n is the number of test points.

A 95% confidence level is used to report the NSSDA. What this means is that 95% of the test points measured on the map will have an error less than or equal to the accuracy level reported with the data. These values are in ground units. If the rms error reported for the map is 1.5 m and the 20 check points were used to determine this rms error, then 19 of those points will have discrepancies less than or equal to 1.5 m. The other point can be larger. This accuracy value will include all uncertainties that can be found in the mapping process.

A minimum of 20 check points are required for the NSSDA. It is also required to distribute those points over the area of interest. If fewer than 20 test points are used then an alternative method is used to check the accuracy of the data set. The Spatial Data Transfer Standards have identified alternative methods, which include deductive estimates, internal evidence, and comparison to source [FGDC, 1998].

While the NSSDA defines the rms error in terms of individual coordinates, it is often convenient to express the accuracy in terms of horizontal and vertical components. From error propagation, the horizontal error can be expressed as

$$\mathrm{rms}_{Hor} = \sqrt{\mathrm{rms}_X^2 + \mathrm{rms}_Y^2}$$

$$= \sqrt{\frac{\sum_{i=1}^{n}\left[\left(X_{Map_i} - X_{Survey_i}\right)^2 + \left(Y_{Map_i} - Y_{Survey_i}\right)^2\right]}{n}}$$

When the errors are the same in both coordinate directions, i.e. $\mathrm{rms}_X = \mathrm{rms}_Y$, then

$$\mathrm{rms}_{Hor} = \sqrt{2\,\mathrm{rms}_X^2} = \sqrt{2\,\mathrm{rms}_Y^2}$$

$$= 1.4142\,\mathrm{rms}_X = 1.4142\,\mathrm{rms}_Y$$

If one assumes that the error is normally distributed and that the errors in each coordinate frame are independent then a factor of 2.4477 is multiplied to the rms error to achieve the 95% confidence level. The accuracy is then shown as

$$\mathrm{Accuracy}_{Hor} = 2.4477\,\mathrm{rms}_X = 2.4477\,\mathrm{rms}_Y$$

$$= \frac{2.4477\,\mathrm{rms}_{Hor}}{1.4142}$$

$$= 1.7308\,\mathrm{rms}_{Hor}$$

When the errors in the two axes are not equal, $\mathrm{rms}_X \neq \mathrm{rms}_Y$, then the accuracy can be approximated by computing the circular standard error (at the 39.35% confidence level) provided that the ratio $\mathrm{rms}_{min}/\mathrm{rms}_{max}$ is between 0.6 and 1.0. The rms_{min} is the smaller value between rms_X and rms_Y whereas rms_{max} is the larger value [FGDC, 1998]. The circular error can be approximated by $0.5\left(\mathrm{rms}_X + \mathrm{rms}_Y\right)$. As before, assuming the error is normally distributed and that the errors in the two coordinates are independent, then the NSSDA can be approximated using

$$\mathrm{Accuracy}_{Hor} \approx (2.4477)(0.5)\left(\mathrm{rms}_X + \mathrm{rms}_Y\right)$$

Table 2. Accuracy Calculations for Crider, Kentucky USGS 1:24,000-scale Topographic Quadrangle ($RMSE_x$ = $RMSE_y$ assumed)

Number	Description	x (computed)	x (map)	diff in x	squared diff in x (1)	y (computed)	y (map)	diff in y	squared diff in y (2)	(1) +(2)	square root of [(1) +(2)]
10351	T-RD-W	1373883	1373894	11	121	298298	298297	-1	1	122	11.05
10352	T-RD-E	1370503	1370486	-17	289	303727	303747	20	400	689	26.25
10353	RD AT RR	1361523	1361537	14	196	302705	302705	0	0	196	14.00
10354	T-RD-SW	1357653	1357667	14	196	298726	298746	20	400	596	24.41
10355	T-RD-SE	1348121	1348128	7	49	299725	299755	30	900	949	30.81
10356	RD AT RR	1345601	1345625	24	576	309911	309910	-1	1	577	24.02
10357	T-RD-E	1350505	1350507	2	4	318478	318477	-1	1	5	2.24
10358	X-RD	1351781	1351792	11	121	307697	307698	1	1	122	11.05
10359	T-RD-E	1352361	1352379	18	324	311109	311099	-10	100	424	20.59
10360	X-RD	1360657	1360645	-12	144	316720	316761	41	1681	1825	42.72
10361	Y-RD-SW	1368215	1368202	-13	169	309842	309869	27	729	898	29.97
10362	T-RD-W	1370299	1370282	-17	289	316832	316849	17	289	578	24.04
10363	T-RD-S	1373855	1373839	-16	256	319893	319886	-7	49	305	17.46
10364	Y-RD-W	1379981	1379962	-19	361	311641	311633	-8	64	425	20.62
10365	T-RD-E	1378625	1378628	3	9	334995	335010	15	225	234	15.30
10366	T-RD-SE	1374735	1374742	7	49	333909	333922	13	169	218	14.76
10367	T-RD-NW	1370581	1370576	-5	25	324098	324095	-3	9	34	5.83
10368	Y-RD-SE	1359379	1359387	8	64	328690	328691	1	1	65	8.06
10369	T-RD-S	1346459	1346479	20	400	330816	330812	-4	16	416	20.40
10370	T-RD-E	1347101	1347109	8	64	335869	335850	-19	361	425	20.62
10371	T-RD-SE	1350733	1350748	15	225	332715	332725	10	100	325	18.03
10372	T-RD-N	1354395	1354411	16	256	335337	335345	8	64	320	17.89
10373	T-RD-S	1358563	1358570	7	49	335398	335406	8	64	113	10.63
10374	X-RD	1365561	1365574	13	169	333873	333877	4	16	185	13.60
10375	X-RD	1373645	1373643	-2	4	339613	339609	-4	16	20	4.47
									sum	10066	
									average	402.64	
									RMSEr	20.07	
									Accuracy per NSSDA (2.4477 * RMSEr)	35	

Table 3. Accuracy Computations for Crider, Kentucky USGS 1:24,000-scale Topographic Quadrangle ($RMSE_x \neq RMSE_y$)

Number	Description	x (computed)	x (map)	diff in x	squared diff in x	y (computed)	y (map)	diff in y	squared diff in y
10351	T-RD-W	1373883	1373894	11	121	298298	298297	-1	1
10352	T-RD-E	1370503	1370486	-17	289	303727	303747	20	400
10353	RD AT RR	1361523	1361537	14	196	302705	302705	0	0
10354	T-RD-SW	1357653	1357667	14	196	298726	298746	20	400
10355	T-RD-SE	1348121	1348128	7	49	299725	299755	30	900
10356	RD AT RR	1345601	1345625	24	576	309911	309910	-1	1
10357	T-RD-E	1350505	1350507	2	4	318478	318477	-1	1
10358	X-RD	1351781	1351792	11	121	307697	307698	1	1
10359	T-RD-E	1352361	1352379	18	324	311109	311099	-10	100
10360	X-RD	1360657	1360645	-12	144	316720	316761	41	1681
10361	Y-RD-SW	1368215	1368202	-13	169	309842	309869	27	729
10362	T-RD-W	1370299	1370282	-17	289	316832	316849	17	289
10363	T-RD-S	1373855	1373839	-16	256	319893	319886	-7	49
10364	Y-RD-W	1379981	1379962	-19	361	311641	311633	-8	64
10365	T-RD-E	1378625	1378628	3	9	334995	335010	15	225
10366	T-RD-SE	1374735	1374742	7	49	333909	333922	13	169
10367	T-RD-NW	1370581	1370576	-5	25	324098	324095	-3	9
10368	Y-RD-SE	1359379	1359387	8	64	328690	328691	1	1
10369	T-RD-S	1346459	1346479	20	400	330816	330812	-4	16
10370	T-RD-E	1347101	1347109	8	64	335869	335850	-19	361
10371	T-RD-SE	1350733	1350748	15	225	332715	332725	10	100
10372	T-RD-N	1354395	1354411	16	256	335337	335345	8	64
10373	T-RD-S	1358563	1358570	7	49	335398	335406	8	64
10374	X-RD	1365561	1365574	13	169	333873	333877	4	16
10375	X-RD	1373645	1373643	-2	4	339613	339609	-4	16
				sum	4409				5657
				average	176.36				226.28
				RMSE	13.28				15.04
				$RMSE_{min}/RMSE_{max}$					0.88

Since $RMSE_{min}/RMSEW_{max}$ is between 0.6 and 1.0, the formula $Accuracy_r \sim 2.4477*0.5*(RMSE_x + RMSE_y)$ may be used to estimate accuracy according to the NSSDA. $Accuracy_r \sim 35$ feet.

Vertical accuracy is approached in a similar vein. Assuming that the errors are normally distributed, to find the accuracy at the 95% confidence interval, multiply the root mean square error by 1.9600. Thus we have

$$\text{Accuracy}_{\text{Ver}} = 1.9600\,\text{rms}_{\text{Z}}$$

Example calculations for horizontal accuracy of a map given $rms_X = rms_Y$ and $rms_X \neq rms_Y$ are shown in tables 2 and 3 respectively [from FGDC, 1998, p. 3-14 and 3-15]. We can see that a simple spreadsheet provides a very useful tool to determining the accuracy standard. A similar spreadsheet could be developed for vertical accuracy determination.

Accuracy determination of map points can only be done when these test points are well-defined. What constitutes a well-defined point depends on the scale of the map and the map product. For vector maps, the point must be recoverable on the ground and on the map itself. Accuracy can only be gauged on how well the mapped position of a well-defined point matches to the corresponding position as determined from a higher accuracy survey.

Distribution of the check points is also critical o ensure that the accuracy reported represents the general characteristics of the area of interest. Therefore, the NSSDA require a minimum spacing between the check points of 10% of the diagonal distance across the mapped area. Moreover, at least 20% of the test points will be located in each quadrant. This means that at least 4 test points shall be located in each quadrant, assuming that 20 test points are used in the evaluation.

Since the NSSDA does not give any conformance criteria, the contracting agency may revert to the NMAS for minimum values to evaluate acceptance of a map. This can be done using the circular error at the 90% confidence level. Greenwalt and Schultz [1968] identify four different circular precision indices, one of which is the Circular Map Accuracy Standard (CMAS). The CMAS can be defined on the basis of the NMAS as [FGDC, 1998]

$$\text{CMAS} = 2.1460\,\text{rms}_{\text{X}} = 2.1460\,\text{rms}_{\text{Y}}$$

$$= \frac{2.1460\,\text{rms}_{\text{Hor}}}{1.4142}$$

$$= 1.5175\,\text{rms}_{\text{Hor}}$$

This relationship assumes a normal distribution and that the errors in the x and y directions are equal and independent. The value 2.1460 is used to compute the 90% confidence level. The CMAS can be reported according to the NSSDA accuracy value as [FGDC, 1998]

$$\text{Accuracy}_{\text{Hor}} = \left(\frac{2.4477}{2.1460}\right)\text{CMAS}$$

$$= 1.1406\,\text{CMAS}$$

Recall that for map scales larger than 1:20,000, the National Map Accuracy Standard is 1/30" at the map scale. This value must be converted to ground scale. The CMAS is then defined as

$$\text{CMAS} = \frac{\left(\tfrac{1}{30}"\right)\left(\tfrac{1'}{12"}\right)}{S} = (0.00278')S_{\text{Den}}$$

where S_{Den} is the denominator of the scale. Then the horizontal accuracy becomes

$$\text{Accuracy}_{\text{Hor}} = 1.1406\,(0.00278')S_{\text{Den}}$$

$$= 0.0032'\,S_{\text{Den}}$$

Using the same approach, the horizontal accuracy for maps at a scale of 1:20,000 or smaller is [FGDC, 1998]

$$\text{Accuracy}_{\text{Hor}} = 0.019'\,S_{\text{Den}}$$

In a similar vein, vertical accuracy can also be determined. Assuming a normal distribution, the factor used to compute the 90% confidence level is 1.6449 [Greenwalt and Schultz, 1968]. Therefore the Vertical Map Accuracy Standard (VMAS) based on the NMAS is [FGDC, 1998]

$$\text{VMAS} = 1.6449\,\text{rms}_Z$$

This can be converted to NSSDA accuracy reporting as

$$\text{Accuracy}_{\text{Vert}} = \left(\frac{1.9600}{1.6449}\right)\text{VMAS}$$

$$= 1.1916\,\text{VMAS}$$

Since accuracy is expressed in terms of the contour interval (CI), the vertical accuracy expressed in terms of NSSDA is

$$\text{Accuracy}_{\text{Vert}} = \left(\frac{1.1916}{2}\right)\text{CI}$$

$$= 0.5958\,\text{CI}$$

The units are derived from the contour interval.

INDUSTRY STANDARDS

Because of problems with the National Map Accuracy Standards (NMAS), the American Society of Photogrammetry and Remote Sensing (ASPRS) approved large-scale mapping accuracy standards [ASPRS, 1990]. The standards are expressed in terms of a limiting root mean square (rms) error which is defined as

$$\text{rms} = \sqrt{\frac{\sum_{i=1}^{n} d_i}{n}}$$

where d is the discrepancy between the mapped coordinate expressed in ground units and the surveyed coordinates, and n is the number of points tested. The rms error is computed for each coordinate. Thus, as an example, the rms error in the X-direction is shown as

$$\text{rms}_X = \sqrt{\frac{\sum_{i=1}^{n} d_i}{n}}$$

$$d_i = X_{\text{map}_i} - X_{\text{survey}_i}$$

Although presented slightly different here, it is identical to the NSSDA given previously.

The ASPRS standard also introduces three classes of maps based on the limiting rms error. Class 1 maps are the highest and are shown, for planimetry, using Imperial units, in Table 4. The metric values are shown in

Table 5. Class 2 maps are those were the acceptable limiting rms error is twice that of Class 1 while Class 3 allow an rms error of three times that in Class 1. The double line in Table 4 represents the limit of mapping using aerial photography. Mapping at the larger scales are usually done using conventional surveying techniques.

Typical Map Scale	Limiting rms error in X or Y		
	Class 1	Class 2	Class 3
1:60	0.05	0.1	0.15
1:120	0.1	0.2	0.3
1:240	0.2	0.4	0.6
1:360	0.3	0.6	0.9
1:480	0.4	0.8	1.2
1:600	0.5	1.0	1.5
1:1,200	1.0	2.0	3.0
1:2,400	2.0	4.0	6.0
1:4,800	4.0	8.0	12.0
1:6,000	5.0	10.0	15.0
1:9,600	8.0	16.0	24.0
1:12,000	10.0	20.0	30.0
1:20,000	16.7	33.3	50.0

Table 4. Planimetric coordinate accuracy requirements (ground X and Y) in feet for well-defined points.

Typical Map Scale	Limiting rms error in X or Y		
	Class 1	Class 2	Class 3
1:50	0.0125	0.025	0.0375
1:100	0.025	0.050	0.075
1:200	0.050	0.100	0.150
1:500	0.125	0.250	0.375
1:1,000	0.25	0.50	0.75
1:2,000	0.50	1.00	1.50
1:4,000	1.00	2.00	3.00
1:5,000	1.25	2.50	3.75
1:10,000	2.50	5.00	7.50
1:20,000	5.00	10.00	15.00

Table 5. Planimetric coordinate accuracy requirements (ground X and Y) in meters for well-defined points.

The limiting rms error for elevations is one-third the value of the contour interval (CI) while for spot heights the value is 1/6 CI. Table 6 shows the vertical accuracy requirements [USACE, 1996]. One obstacle exists with vertical accuracy and that is defining a point from which the comparison is to be made. Contours are not well-defined in the same sense as planimetry. Thus, well-defined points can be found on the imagery and its height would be interpolated from the contour elevations. A second issue is vertical accuracy for digital elevation models. Since vertical accuracy is a function of the contour interval, it will be necessary to generate an equivalent CI. This value can be defined through the accuracy required for the project.

Testing for compliance is done by comparing the mapped position at ground scale to the location of the points determined from a survey of higher accuracy. That survey must be designed using Federal Geodetic Control Subcommittee (FGCS, formerly FGCC - Federal Geodetic Control Committee) standards and specifications for surveying with a standard deviation no greater than 1/3 of the limiting rms error. The FGCS standards use the horizontal distance between points in the determination of accuracy. These distance accuracy standards are shown in Table 7. This can be represented by

$$a = \frac{d}{s}$$

where a is the distance accuracy denominator (1:a),
d is the distance between points, and
s is the standard deviation of the distance as determined from a least squares adjustment.

Target CI, ft.	Limiting rms errors					
	Topographic feature points for class			Spot or Digital Terrain Model Elevation point for class		
	1	2	3	1	2	3
0.5	0.17	0.33	0.5	0.08	0.16	0.25
1	0.33	0.66	1.0	0.17	0.33	0.50
2	0.67	1.33	2.0	0.33	0.67	1.00
4	1.33	2.67	4.0	0.67	1.33	2.00
5	1.67	3.33	5.0	0.83	1.67	2.50

Table 6. Height/Elevation accuracy requirements [from USACE, 1996].

Classification	Minimum Distance Accuracy
First-Order	1:100,000
Second-Order, Class I	1: 50,000
Second-Order, Class II	1: 20,000
Third-Order, Class I	1: 10,000
Third-Order, Class II	1: 5,000

Table 7. Distance accuracy standards.

The distance used to evaluate the accuracy of the map is the diagonal distance across the map sheet. From the example in ASPRS [1990], if the diagonal distance on the map is 6,000 feet and the scale is 1:1200 then the limiting rms error is 1'. Since the survey used for comparison needs to be no more than 1/3rd of the limiting rms error, this means that the check survey needs to have an accuracy level of 0.33'. Then, the denominator of the distance accuracy is

$$a = \frac{d}{s} = \frac{6{,}000'}{0.33'} = 18{,}182'$$

From Table 7, it can be seen that a survey conducted to Second-Order, Class II specifications will be necessary to check this map.

Vertical control surveys used to check mapping have slightly different kinds of criteria. First of all, the planimetric position of the map point can be shifted up to twice the limiting rms error. Second, the level check survey must be conducted such that the rms error in elevation at the check point does not exceed 1/20th of the contour interval. Like the planimetric survey, this standard is dependent upon the distance (d) between bench marks. Again, like the planimetric standard, this distance can be taken to the diagonal distance across the map.

The elevation difference accuracy (b) is defined as

$$b = \frac{s}{\sqrt{d}}$$

where d is the distance between control points and s is the standard deviation of the elevation difference between control points determined from a least squares adjustment. The units of b are in mm/□km. The classification of elevation accuracy standards is given in Table 8.

Classification	Maximum Elevation Difference Accuracy
First-Order, Class I	0.5
First-Order, Class II	0.7
Second-Order, Class I	1.0
Second-Order, Class II	1.3
Third-Order	2.0

Table 8. Elevation accuracy standard.

Using the same example as presented by ASPRS [1990], assume that the contour interval was determined to be 2 feet, then

$$s = \frac{1}{20}\,CI = 0.10'$$

from which[3]

$$b = \frac{s}{\sqrt{d}} = \frac{(1.20'')\left(12\,\mathrm{in}/\mathrm{ft}\right)\left(25.4\,\mathrm{mm}/\mathrm{in}\right)}{\sqrt{(600')\left(\frac{1200\,\mathrm{m}}{3937\,\mathrm{ft}}\right)\left(\frac{1\,\mathrm{km}}{1000\,\mathrm{m}}\right)}} = 22.5\ \mathrm{mm}/\sqrt{\mathrm{km}}$$

From Table 5 it is clear that a Third-Order level survey would suffice in this case, and in most mapping applications.

If discrepancies in any of the coordinates exceed three times the limiting rms error, the assumption is that this difference is due to a blunder and must be corrected before the map can pass the standard. Also, the APSRS standard requires that a minimum of 20 points be used for comparison purposes. It is up to the contracting parties to agree on their distribution.

Both the ASPRS standards and the National Standard for Spatial Data Accuracy use the root mean square error in their evaluation. Since the NSSDA reports the accuracy at the 95% confidence level, the ASPRS standard needs to be modified in order to report the results based on the NSSDA. The relationship between the rms and accuracy was shown in the section discussing the NSSDA.

3 Note that the ASPRS article gives the distance d = 6,000' = 0.181 l km. But the conversion should be, as shown above, d = 6000' = 1.8288 km. The conclusions, though, are the same.

The Engineering Map Accuracy Standards (EMAS) actually were the precursor to the ASPRS standards. The idea was to provide a set of standards that were better suited for large-scale mapping. Additionally, they provided more flexibility than the NMAS that were already being used in the mapping community. Unlike the ASPRS standards, the EMAS did not specify thresholds to be achieved in the mapping (this is like the NSSDA). In other words, accuracy levels were only identified. It was up to the contracting agency to establish minimum criteria for the map.

The EMAS utilize two different allowable or limiting errors: limiting standard error and limiting mean absolute error. They also introduced statistical testing to ensure compliance. Two statistical tests were employed: t-distribution and the χ^2 (Chi^2) distribution.

The limiting standard error, also called the standard deviation σ_0, is found by comparing the mapped position converted to the ground scale to the corresponding values obtained from an independent survey of higher accuracy. The estimated value of the limiting standard error is designated as "s" and it is shown mathematically as:

$$s_X = \sqrt{\frac{\sum_{i=1}^{n}\left(\delta X_i - \overline{\delta X}\right)^2}{n-1}} \qquad s_Y = \sqrt{\frac{\sum_{i=1}^{n}\left(\delta Y_i - \overline{\delta Y}\right)^2}{n-1}}$$

$$s_Z = \sqrt{\frac{\sum_{i=1}^{n}\left(\delta Z_i - \overline{\delta Z}\right)^2}{n-1}}$$

where: δ_I = the discrepancy between the mapped point and its corresponding position determined from a survey of higher accuracy,

$\bar{\delta} = \frac{\sum_{i=1}^{n}\delta_i}{n}$, and

n = the number of points tested, assumed to be greater than or equal to 20.

The limiting standard error is used to measure the precision of the mapping. Using the χ^2 distribution at the 95% confidence interval $(1 - \alpha)$ and a one-tailed test, the precision is evaluated by hypothesis testing.

The limiting mean absolute error is also called the limiting absolute error of the mean deviation, $\left|\bar{\delta}_o\right|$. This is found by using the absolute value of the discrepancy between the mapped position and the corresponding position from a survey of high accuracy. The purpose of the limiting mean absolute error is to determine if any bias exists. It is defined mathematically as:

$$\left|\delta X\right| = \left|\frac{\sum_{i=1}^{n} \delta X_i}{n}\right| \qquad \left|\delta Y\right| = \left|\frac{\sum_{i=1}^{n} \delta Y_i}{n}\right| \qquad \left|\delta Z\right| = \left|\frac{\sum_{i=1}^{n} \delta Z_i}{n}\right|$$

hypothesis testing of the limiting mean absolute error is performed using the t-distribution, or student-t distribution, at the 95% confidence interval (1 - α) and a one-tailed test.

Compliance testing is important for any type of measurement process. Within the EMAS, it is assumed that if any of the discrepancies exceed three times the specified limiting standard error then that measurement is a blunder and must be remeasured. For example, if the client specified that the limiting standard error is 1' and a difference between a mapped position to the corresponding position from a higher order survey was 4' then a blunder is present. The only way a blunder can be corrected is by remeasuring the point.

The other issue related to compliance testing is the distribution of the check points. The goal is to obtain a wide distribution over the desired mapped area. The EMAS specify that the spacing between the check points must be a minimum of 1/12 of the diagonal distance of the mapped region and a maximum of 1/4 the diagonal distance. Hence, if the area of the mapping covers a rectangle of 2,500' x 2,000' then the diagonal distance is $\sqrt{(2{,}500')^2 + (2{,}000')^2} = 3{,}202'$. The minimum and maximum spacing are 267' and 800' respectively. Additionally, at least 15% of the check points must be located in each quadrant of the mapped area. For 20 check points this means that at least 3 must be in each quadrant of the map. It may happen that one or more of the quadrants do not have enough well-defined detailed points in the area to perform the compliance testing. In this situation targets will be distributed within the area for use in measurement testing.

When discrepancies occur, the cause of this deviation can be attributed to two sources, namely errors in the mapping and errors in the check survey. The survey must be of sufficient accuracy such that the compliance testing reflects the majority influence of the errors in the mapping. Therefore, the EMAS specifies that the error within the survey cannot exceed 1/3rd the specified limiting standard error or the limiting mean absolute error.

STATE STANDARDS

Missouri mapping standards are identical to the ASPRS large-Scale Mapping Standards. Both horizontal and vertical accuracy is expressed in three different classes like ASPRS [Missouri DNR, 2001].

New Jersey Department of Transportation (NJDOT) has developed photogrammetric mapping standards that are similar to the NMAS in that a 90% error is used. Comparison of position, though, is done at ground scale. In addition, NJDOT have established a maximum limit of acceptable error for the remaining 10% of tested points. Their standards of accuracy are given in Table 9.

SCALE	**CONTOUR INTERVALS**	**CULTURAL FEATURES**	**CONTOURS**	**SPOT ELEVATIONS**	**MAXIMUM SHEET SIZE**
1"=200'	Five feet; accentuate each 25 ft. contour	90% shall be within 5' of the actual position; 10% shall not exceed 10.0' of actual position	90% shall not exceed 2.50' of the actual elevation; 10% shall not exceed 5.0' of actual elevation.	90% shall not exceed 1.25' of the actual elevation; 10% shall not exceed 2.5' of the actual elevation.	5.0 feet long and 2.5 feet wide.
1"=100'	Two feet; accentuate each 10 ft contour.	90% shall be within 2.5' of the actual position; 10% shall not exceed 5.0' of the actual position.	90% shall not exceed 1.00' of the actual elevation; 10% shall not exceed 2.0' of the actual elevation.	90% shall not exceed 0.50' of the actual elevation; 10% shall not exceed 1.0' of the actual elevation.	5.0 feet long and 2.5 feet wide.

1"=50'	One foot; accentuate each 5 ft contour.	90% shall be within 1.0' of the actual position; 10% shall not exceed 2.0' of the actual position.	90% shall not exceed 0.50' of the actual elevation; 10% shall not exceed 1.0' of the actual elevation.	90% shall not exceed 0.25' of the actual elevation; 10% shall not exceed 0.5' of the actual elevation.	5.0 feet long and 3.5 feet wide.
As determin ed	As determined	90% shall be within 1/40th of the map scale actual position; 10% shall not exceed 1/20th of the map scale actual position.	90% shall not exceed one half of the contour interval of the actual elevation; 10% shall not exceed one contour interval of the actual elevation.	90% shall not exceed one quarter of the contour interval of the actual elevation; 10% shall not exceed one half of the contour interval of the actual elevation.	As determined

Table 9. Standards of Accuracy for Photogrammetric Mapping from the New Jersey Department of Transportation [**http://www.state.nj.us/dep/gis/resource/appenez.htm**].

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