Issue 50: Phase III Quality Control of Light Detection and Ranging (LIDAR) Elevation Data in North Carolina

Background

Reference Appendix A, *Guidance for Aerial Mapping and Surveying*, of FEMA's Guidelines and Specifications for Flood Hazard Mapping Partners at www.fema.gov/mit/tsd/dl_cgs.htm, and the National Standard for Spatial Data Accuracy (NSSDA) which specifies that accuracy of geospatial data be reported in ground distances at the 95% confidence level. The requirements for digital elevation data for flood insurance studies should be determined early in the process. Typically, for hydraulic modeling, FEMA specifies that elevation data equivalent to 4' contours ($RMSE_z$ = 1.2 ft (37 cm); $Accuracy_z$ = 2.4 ft (72.5 cm) at 95% confidence level) are appropriate for rolling to hilly terrain, and elevation data equivalent to 2' contours ($RMSE_z$ = 0.6 ft (18.5 cm); $Accuracy_z$ = 1.2 ft (36.3 cm) at 95% confidence level) are appropriate for flat terrain. FEMA encourages its own Project Officers, as well as Cooperating Technical Partners and States, to establish practical accuracy requirements for digital elevation datasets consistent with technical requirements and funds available.

For Phase I of the North Carolina Floodplain Mapping Program (NCFMP) initiated in 2000, the state specified a vertical RMSE ($RMSE_z$) of 20 cm for coastal counties and $RMSE_z$ of 25 cm for inland counties, computed after deletion of the worst 5% of the checkpoints. This is equivalent to vertical accuracies ($Accuracy_z$) of 1.3 ft (39.2 cm) and 1.6 ft (49.0 cm), respectively, at the 95% confidence level, except that all accuracy assessments for Phase I were based on the best 95% of the checkpoints rather than the entire population of checkpoints. In 2000, the state had no better way to accommodate the fact that up to 5% of the checkpoints might not follow a normal error distribution required for the RMSE process to be applicable. There were no published alternatives at the time, other than accepting the fact that, by utilizing 100% of the checkpoints, even a single outlier could totally skew the RMSE calculations and accuracy assessments derived therefrom. Since the majority of Phase I LIDAR datasets had error distributions that did not follow a normal distribution, this demonstrated the validity of not using RMSE calculations for all 100% of the checkpoints because this would have unduly skewed the accuracy statistics.

In 2002, the National Digital Elevation Program (NDEP) established draft guidelines that specifically address LIDAR and the fact that the RMSE process is inappropriate for many land cover categories except for open terrain where there are no valid reasons why errors should not follow a normal error distribution. Version 1.0 of the final NDEP guidelines were published on May 10, 2004 (see http://www.ndep.gov/NDEP_Elevation_Guidelines_Ver1_10May2004.pdf) entitled: "Guidelines for Digital Elevation Data." The NDEP guidelines specify *Fundamental Vertical Accuracy* at the 95% confidence level, computed by multiplying the $RMSE_z$ by 1.9600, for open terrain only; this establishes the fundamental accuracy of the LIDAR sensor in open terrain. Additionally, the NDEP establishes both *Supplemental Vertical Accuracy* for other individual land cover categories, and *Consolidated Vertical Accuracy* in all land cover categories combined, using the 95th percentile errors to determine vertical accuracy at the 95% confidence level. This allows 5% of the checkpoint errors to exceed the established standard for $Accuracy_z$. The *Supplemental Vertical Accuracy* establishes the vertical accuracy in land cover categories, other than open terrain, where there may be legitimate reasons why errors do not follow a normal distribution; this determines how well the sensor performed, as well as the effectiveness of the post-processing used to establish "bare earth" elevations. The *Consolidated Vertical Accuracy* does the same for all combined land cover categories representative of the area being mapped.

For Phase II of the NCFMP, the state has specified *Fundamental Vertical Accuracy* of 1.2 ft (36.3 cm) in open terrain, and Consolidated Vertical Accuracy of 1.6 ft (49.0 cm) in all land cover categories combined, including open terrain, weeds and crops, scrub, forests, and urban terrain (built-up areas). The state has also specified horizontal (radial) accuracy ($Accuracy_r$) of 5.68 ft (1.73 m) at the 95% confidence level, which is equivalent to a horizontal (radial) RMSE ($RMSE_r$) of 3.28 ft (1 meter). These same specifications pertain to Phase III.

Recommendations

The North Carolina mapping effort should follow the procedures discussed below to ensure quality control of the digital elevation data being obtained.

Phase 1: Independent Quality Control Checkpoints

1.1 Land Cover Categories: Working with the North Carolina Center for Geographic Information and Analysis (CGIA), the North Carolina Geodetic Survey (NCGS) will categorize all land into one of five major land cover categories representative of the floodplains: a) open terrain (e.g., bare-earth, sand, rock, plowed fields, short grass, golf courses); b) high grass, weeds, and crops (e.g., hay, corn, wheat, tobacco); c) brush lands and low trees; d) fully forested; and e) urban areas (vicinity of manmade structures, preferably high density).

1.2 Checkpoint Selection: For each county, NCGS will direct independent survey contractors to select 20 or more checkpoints, in each of the five land cover categories, except for forested areas where 40 checkpoints will be surveyed. Each checkpoint should be on terrain that is flat or uniformly sloping within 5 meters in all directions (i.e., no breaklines within 5 meters of the checkpoint). CGIA will provide county maps of land-cover categories, and the survey contractors will be provided with large-area polygons dispersed throughout each county within which the surveyors will select the checkpoints. Where possible, checkpoints should be interspersed throughout a county area so that checkpoints will cover different flightlines. For example, if LIDAR flightlines are generally north-south, it is ideal for surveyors to survey in the vicinity of east-west roads in order to disperse checkpoints to cover different flightlines. The checkpoints in urban areas should be located, if possible, on clearly defined points expected to be visible on LIDAR intensity images, e.g., where a paint stripe on a road intersects with a curb line; recognizing that some points in urban areas may subsequently prove to be invisible on the LIDAR intensity image, those that are visible will be used to evaluate the LIDAR horizontal accuracy ($Accuracy_r$) in addition to its vertical accuracy ($Accuracy_z$).

1.3 Checkpoint Surveys: NCGS will contract for independent surveys of all checkpoints to 5-cm Local Network accuracy according to NOAA Technical Memorandum NOS NGS-58, "Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm)," Version 4.3, November 1997 (referred to as NGS-58). Monuments selected for differential GPS base stations should have the best available Vertical Order, Stability C or better, with preference given to NC HARN monuments. If selected monuments are farther than 20 km from the test areas to be surveyed, Secondary Base Stations will be established so that final surveys of checkpoints will satisfy NGS-58 requirements for Local Network accuracy of 5-cm at the 95% confidence level. Alternatively, GPS RTK may be used provided: (1) the DGPS base station is an existing NGS 3-D mark or a new NGS-58 mark; (2) RTK can only be used in open areas, and each RTK point must be occupied twice on different days and at different times of the day. The purpose is to ensure different atmospheric conditions and significantly different satellite geometry (3) the difference between observations must not exceed 5 cm. Network RTK may be used in areas that this service is available. Items (2) and (3) under traditional RTK must be followed when using Network RTK. Online Processing User Service (OPUS) can be used if the contractor obtains written approval from NC Geodetic Survey. Third-order conventional surveys may be used to extend control from open areas (surveyed by GPS) to forested areas where GPS signals are blocked. These checkpoints will be used for the official vertical accuracy assessments (Fundamental Vertical Accuracy and the Consolidated Vertical Accuracy) of the bare-earth LIDAR data after post processing.

1.4 Cluster Survey Points: Additional survey measurement should be included where possible surrounding the control point being established for the vertical comparisons in vegetated areas. This will include both conventional methods and RTK. For RTK surveys, additional surrounding points within a few meters of the new control point should be established to help identify whether the LIDAR penetrated the vegetated surface. The same procedure can be utilized for conventional surveys. While the total station is set up, the survey instrument person could move a few meters in each direction to collect additional measurements. These additional cluster points will not be used for vertical accuracy assessments, but they will be used to evaluate artifacts and cleanliness.

1.5 Cross Section Surveys: A total of __ cross sections of varying terrain will be measured. Ideally stream channels should be measured but will not include underwater measurements. If streams cannot be measured, undulating terrain or drainage ditches exceeding 3 meter width could be measured using RTK. Measurements could be taken at two meter intervals for 50 meters over undulating terrain. These cross section surveys will not be used for official vertical accuracy assessments, but they will be used to assess the bare-earth mass points to ensure that post-processing did not overly flatten stream channel geometry (stream banks) used for hydraulic modeling.

1.6 Documentation: The survey company will mark each checkpoint with a 60d nail or larger. The station ID number will be written on an adjacent above-ground stake within 1 foot of the referenced stake. "To reach" descriptions and photographs will be used to document the location, the land cover surrounding each stake, and the uniform slope of the terrain surrounding each stake. A full report will be required outlining the methodology of the data collection, the equipment used, software, full output of duplicate point comparisons, least squares adjustment and any information pertinent to the survey. FGDC metadata will also be included with the final coordinates.

1.7 Orthometric Heights: Geoid03 will be used to convert GPS ellipsoid heights into orthometric heights for each checkpoint, using NAVD 88, the specified vertical datum.

1.8 3-D Coordinate Files: The surveyor will provide NCGS with Microsoft Excel 3-D point files (x/y/z values) by State Plane coordinates (U.S. survey feet) to 2 decimal places for the checkpoint surveys, cluster point surveys, and cross section surveys along with a code of the method used to derive the coordinate value (i.e. GPS or conventional survey).

1.9 Security: NCGS will ensure that these 3-D coordinate files are secured and not made available outside of NCGS prior to receipt of the post-processed LIDAR data.

Phase 2: LIDAR Accuracy Assessment

2.1 LIDAR Acquisition Plans: The LIDAR vendor will provide NCGS with acquisition planning information, including, but not limited to, flightline directions, types of sensors, pulses per second, flying altitude above mean terrain, swath width, average point spacing, maximum positional dilution of precision (PDOP), maximum airborne GPS baselines, and sidelap percentage.

2.2 LIDAR Acquisition Data: Upon request, the LIDAR vendor will provide NCGS with actual data for each sensor on each day, to include daily calibration checks, flying altitude, average point spacing, maximum PDOP, maximum GPS baselines, etc., plus maps showing actual flightlines and swaths, by dates acquired and sensors (when multiple LIDAR systems are used). In addition to vertical calibration data, the daily calibration checks will also report the horizontal accuracy of the LIDAR data acquired with flight parameters and sensor settings comparable to those used each day for data acquisition. The results of each daily calibration check will be provided to NCGS by the end of the second business day following data acquisition to ensure calibration data are actually processed in a timely manner.

2.3 Bare Earth Data: The LIDAR vendor will post-process the LIDAR data to generate bare earth 3-D ASCII files or Triangulated Irregular Network (TIN) files.

2.4 Interpolated z-values: When notified that the ASCII/TIN data are complete, NCGS will provide 2-D (x/y coordinates without z-values) of all checkpoints per land cover category to the LIDAR vendor. The vendor immediately (within a few minutes) computes the interpolated LIDAR z-values for the x/y coordinates of the checkpoints and provides 3-D (x/y/z) files to NCGS. Fewer than 20 checkpoints may be allowed in some land cover categories, if difficulty is encountered in finding certain vegetation groups.

2.5 Checkpoint Elevation Discrepancies: The NCGS will prepare Excel spreadsheets with checkpoint elevation discrepancies (z-values interpolated from LIDAR TIN minus z-values from surveyed checkpoints) separated by land cover categories. NCGS will draft values for Fundamental, Consolidated, and Supplemental vertical accuracies.

2.6 Fundamental Vertical Accuracy Test: Using only the checkpoints in open terrain, Dewberry will compute the $RMSE_z$ of the bare-earth LIDAR dataset and compare with values computed by NCGS. If the $RMSE_z$ value is equal to or less than 0.6 ft (18.5 cm), then this test passes and the Fundamental Vertical $Accuracy_z = 1.9600 \times RMSE_z$; proceed to step 2.7. If the $RMSE_z$ is larger than the specified RMSE, there may be systematic errors or problem with the LIDAR sensor and/or parameters used for post processing. All systematic errors need to be corrected and the dataset resubmitted for re-evaluation with additional checkpoints. Since there is no vegetation to be removed in post processing, there should be no excuse for the LIDAR dataset not performing to specifications in open terrain.

2.7 Supplemental Vertical Accuracy Tests: For each of the other four land cover categories, Dewberry will determine the 95th percentile error separately by land cover category and compare with values computed by NCGS. The 95th percentile equals the Supplemental Vertical Accuracy at the 95% confidence level by individual land cover category. Although there is no standard to be met, any individual land cover category with a 95th percentile error significantly larger than 1.6 ft (49.0 cm) is an indication that there may be a systematic problem in post-processing the LIDAR data for that type of land cover. Such information is valuable in trouble-shooting should the Consolidated Vertical Accuracy test fail.

2.8 Consolidated Vertical Accuracy Test: Using all checkpoints in all five land cover categories combined, Dewberry will determine the 95th percentile error for the consolidated dataset and compare with values computed by NCGS. The 95th percentile equals the Consolidated Vertical Accuracy at the 95% confidence level for all land cover categories combined. If the Consolidated Vertical Accuracy is better than 1.6 ft (49.0 cm), then the dataset passes; if not, the dataset fails. For each dataset, Dewberry will also evaluate the error outliers that are larger than the 95th percentile. Outliers larger than 6.6 ft (2 meters) will be cause for investigation by the LIDAR provider to explain the large errors, but such outliers will not necessarily cause the dataset to fail. These will be evaluated on a case-by-case basis by Dewberry and NCGS. Dewberry will document the magnitude of the errors that are larger than the 95th percentile.

2.9 Vertical Accuracy Assessment and Reporting: Dewberry will prepare a LIDAR Accuracy Assessment Report that reports the following:

a) Map with location of checkpoints, color-coded by land cover category
b) Fundamental Vertical Accuracy at 95% confidence level in open terrain using $RMSE_z$ x 1.9600, compared with the 1.19 ft specification.
c) Consolidated Vertical Accuracy at 95th percentile in all land cover categories combined, compared with the 1.61 ft specification.
d) Supplemental Vertical Accuracy at 95th percentile, reported separately for open terrain, weeds and crops, scrub, forest, and built up areas, compared with the target of 1.61 ft.
e) Graphs showing the 95th percentile errors and RMSE errors, graphed separately for each of the five land cover categories
f) Magnitude of outliers larger than the 95th percentile, by land cover category
g) Graph that illustrates the magnitude of the differences between the checkpoints and LIDAR data by specific land cover category, sorted from lowest to highest
h) Overall descriptive statistics to include RMSE, mean, median, skew, standard deviation, minimum and maximum errors, for each land cover category
i) Histogram showing the frequency of checkpoint elevation differences, normally by 1 cm increments between the largest negative error and the largest positive error. This helps to visualize the outliers and proximity to a normal error distribution.

Phase 3: Error Assessments

3.1 Assessments by Land Cover: The causes for the data to not pass the accuracy criteria differ according to land-cover category. Typically, data in category "a" (open terrain) should pass the Fundamental Vertical Accuracy criteria unless there is a systematic problem; however, the daily calibration checks should confirm that the system performed well at the test site (on that same day with the same sensor), and the test site should be on bare terrain or short grass only. If the Consolidated Vertical Accuracy value is higher than the 1.6 ft (49.0 cm) standard, whereas the Fundamental Accuracy test passed the 1.2 ft (36.3 cm) standard, errors in post-processing need to be corrected, and the individual Supplemental Vertical Accuracy assessments should assist in trouble shooting. If Supplemental Vertical Accuracy tests are considerably higher than 1.6 ft (49.0 cm) for land cover categories "c" (scrub) or "d" (forests), the most probable causes are shortcomings in the vegetation-removal procedures. If the Supplemental Vertical Accuracy tests are considerably higher than 1.6 ft (49.0 cm) for land cover category "e" (urban areas), the most probable cause is a systematic problem with handling buildings or abnormal responses from asphalt.

3.2 Assessments by Error Locations: Dewberry will evaluate the location of significant errors to see if they are consistent throughout the area and to determine where these errors are located within the flightline (e.g., near the beginning or end of swaths).

3.3 Assessments by Dates/Sensors: Dewberry will evaluate the datasets to see if errors are distinguishable by dates or by individual sensors.

3.4 Accuracy Assessment Report: If the above assessments do not yield the probable source of systematic errors, Dewberry will prepare an Accuracy Assessment Report indicating that the LIDAR data did not pass the accuracy criteria. This report will include the same type of information in task 2.9 above, but with a printout of z-value errors, sorted by elevations, without x/y coordinates. The report may identify polygons within which major errors are clustered, to assist in trouble-shooting. The report may recommend that NCGS spot check the elevations on several of the independent checkpoints that yielded the poorest results when compared with the interpolated LIDAR elevations, or the report may recommend that the LIDAR vendor assess the quality of individual components (airborne GPS, inertial measuring unit (IMU), and laser ranges) as well as the integrated system, with technical assistance from the MCC, if requested.

3.5 Airborne GPS Verification: The LIDAR vendor will examine GPS flight trajectories, verify the Positional Dilution of Precision (PDOP) and/or Vertical Dilution of Precision (VDOP), verify GPS satellite residuals, verify the satellite phase RMS, compare forward and reverse flight trajectories' combined separation, verify weighting adjustments when two or more differential base stations are used, verify the base station distance separation, verify position standard deviations, check satellite health, check geo-magnetic observations, verify that the correct vertical datum was used, and verify the correct application of the Geoid99 calculation of orthometric heights.

3.6 IMU Verification: The LIDAR vendor will review the Kalman filter, the measurement residual ratio (MRR), and the consecutive measurement rejections settings; confirm that the IMU was in "fine align" mode for the whole of the data set; check accelerometer drift and scale factor and gyro drift and scale factor to ensure that they are within specifications; compare GPS trajectory with re-computed IMU trajectory and investigate large discrepancies; and review IMU to lever arm parameter measurements and ensure that they are entered correctly in the proper reference system.

3.7 Laser Range Verification: The LIDAR vendor will review raw laser ranges; identify areas of high dropouts (no returns) and correlate them to justifiable features; review scanner mirror angles (galvanometers or micro-controller) LSR reports; examine intensity images; and review system-generated error log sheets.

3.8 Total System Verification: The LIDAR vendor will review daily calibration checks and compare to system flight parameters; use CAD software to analyze flight lines and verify pitch, roll, and heading errors; check overlap for roll and scaling errors; check ground features for pitch (e.g., buildings, bridges); if water bodies exist, check scaling errors; compare cross flight data for attitude; review parameters if data were "corrected" or adjusted for pitch, roll, and heading errors; and verify vegetation removal procedure.

3.9 Systematic Error Corrections: If systematic errors are found, the data will be reprocessed by the LIDAR vendor, with clear written explanations provided to NCGS for review by Dewberry. If no systematic errors are found, the process moves to Phase 4 discussed below.

3.10 Recalculation of Accuracy Statistics: Using additional QC checkpoints, the LIDAR vendor will interpolate the LIDAR dataset for the new checkpoints' 2-D (x/y) coordinate values and provide 3-D (x/y/z) files for recomputation of Fundamental Vertical Accuracy and Consolidated Vertical Accuracy. The results will be provided by NCGS to Dewberry. NCGS may task the QC contractor to collect additional points from those points held in reserve.

3.11 LIDAR Accuracy Assessment Report: If the new calculations from task 3.10 pass the accuracy criteria, Dewberry will prepare a LIDAR Accuracy Assessment Report indicating this fact. If the new calculations do not pass the accuracy criteria, a provisional Accuracy Assessment Report will document the new statistics and recommend alternatives (when pre-approved by NCGS) listed in Phase 4. Dewberry will provide this report to NCGS, and NCGS will provide the report, with additional comments as appropriate, to the mapping contractor.

Phase 4: Final Resolution of Problems

4.1 Provisional LIDAR Accuracy Assessment Report: As coordinated by Dewberry with NCGS, the provisional Accuracy Assessment Report will document the accuracy assessments and recommend resolution to problems identified.

4.2 LIDAR Vendor Checkpoints: The LIDAR vendor will provide NCGS with checkpoints used to validate the LIDAR adjustments, so that NCGS can determine the proximity of the LIDAR vendor checkpoints to the NCGS checkpoints or perform independent surveys of the vendor's checkpoints.

4.3 LIDAR Vendor Control Points: The LIDAR vendor will provide NCGS with control points and/or Least Squares Adjustments used to define the control points for the LIDAR processing. This will allow the NCGS to perform an independent analytical assessment of the vendor's control points to determine if there are any fundamental flaws or discrepancies in the control used for the project area. If the control points are inaccurate, the LIDAR vendor will need to resolve the control point(s) issue and reprocess the LIDAR data to fit the new control values. If the control points used are accurate, then 4.4 shall be implemented.

4.4 Potential Resurveys of NCGS Checkpoints: The LIDAR vendor will be provided with all of NCGS' 3-dimensional coordinates with supporting documentation and will be afforded the opportunity to independently survey and analyze the checkpoints used for the RMSE and 95th percentile calculations at the vendor's expense. If discrepancies are found with the NCGS coordinates, NCGS will rectify the problem and reassess the LIDAR data. If no discrepancies are found, the vendor shall comply with NCGS results and establish procedures to correct the LIDAR data through re-processing and/or reacquisition of the data.

4.5 Potential Reacquisition of LIDAR: NCGS may decide that the LIDAR vendor be allowed to re-fly the area and acquire a new LIDAR dataset, perhaps with shorter GPS baselines, lower PDOP values, lower flying altitude, narrower swath widths, etc. This would normally be performed at the LIDAR firm's expense.

4.6 Detailed Ground Surveys: The LIDAR firm may be offered the opportunity to perform extensive ground surveys of cross sections to satisfy the data needs for hydraulic modeling.

Phase 5: Additional Quality Assessments

For Phase II and Phase III LIDAR acquisitions, LIDAR vendors have been tasked to provide two additional deliverables: LIDAR intensity images, and shaded relief images of selected sample bare-earth mass point tiles.

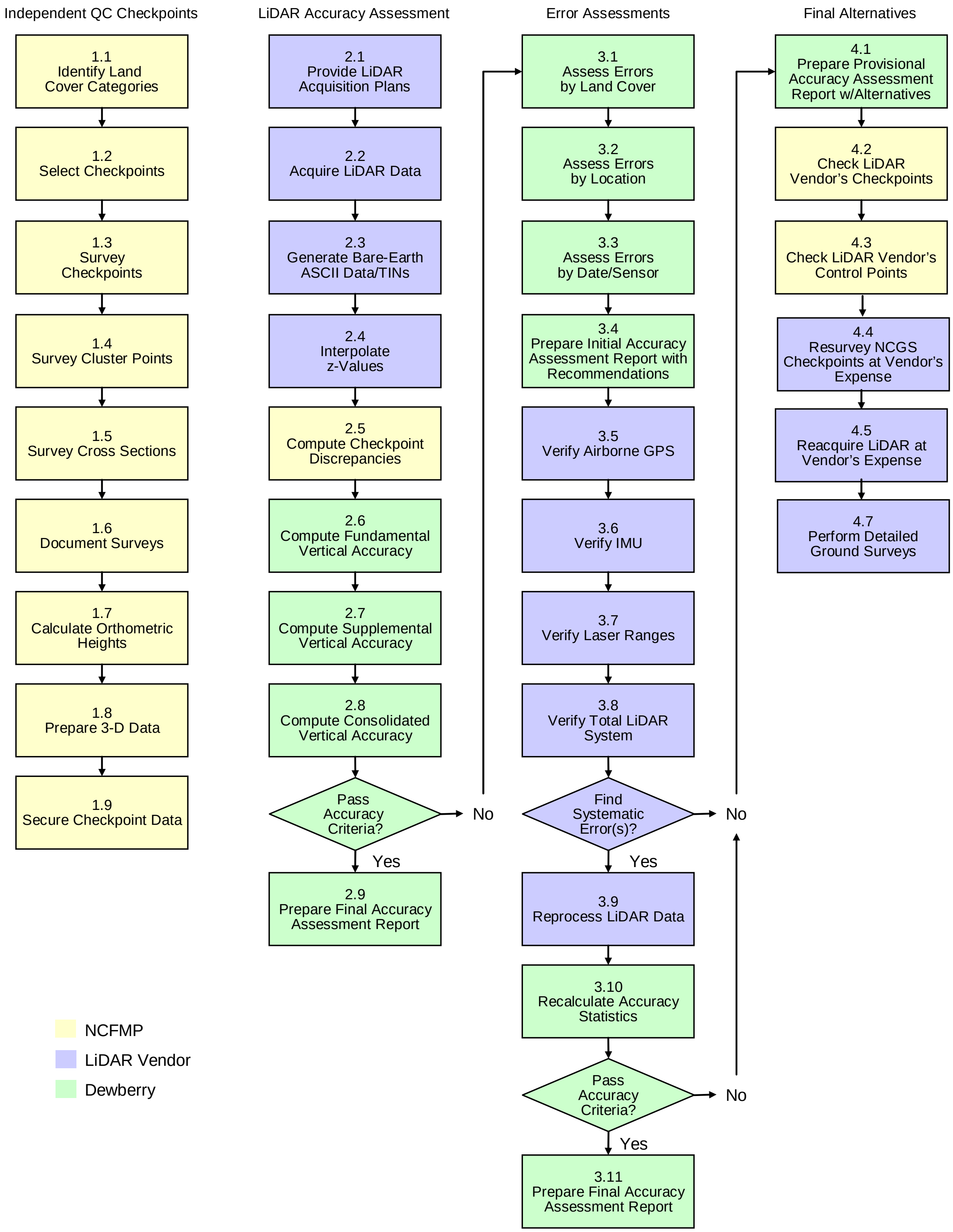
5.1 Intensity Images: In addition to the intensity images being used by the LIDAR vendor to assist in post-processing vegetation removal, the NCGS will request samples of intensity images at the urban area checkpoints so as to evaluate the horizontal accuracy of the LIDAR data, for comparison with the LIDAR vendor's own assessment of horizontal accuracy based on periodic calibration checks.

5.2 Assessment of Cross Sections. Cross sections of survey breakpoints along a stream channel will be compared to the corresponding cross section derived from the TIN. Using the survey cross sections, the horizontal component of the line derived from the survey points will be draped over the TIN. Interpolated elevation values will be generated from the intersection of the line with the vertices of the TIN and a new TIN cross section will result. Comparisons will be made between the surveyed cross section and the interpolated TIN Cross section. Differences will be measured at the breakpoints of the surveyed cross sections. Values greater than 49.3 cm will be evaluated on a case by case basis.

5.3 Assessment of Edge Matching. Edge matching will be tested with a variety of comparative methods. These methods will include a vector and/or a raster approach. If the data was flown with the same sensor, and the post processing procedures are consistent, very little change should be visible along seam edges. One method will be to compare the density of points within a given grid size (i.e. 20 ft.) along the tile boundaries. Significant discrepancies of point densities between adjacent tiles will flag further analysis. A second approach will be to build the TIN of each tile and compare the number of TIN triangles to the adjacent tile, or build a TIN of one tile including a 100 foot buffer of points from the adjacent TIN. Significant differences will again be flagged for review. A third approach would be to use a raster technique and create a TIN GRID. Visually the tile edges should be fairly seamless due to the interpolation of tile edges. Secondary to this, adjacent pixels along seam edges can be compared for elevation differences.

5.4 Assessment of superfluous elevations. Elevations will have a minimum and maximum value that should reflect the true range of the surface being measured. LIDAR at times can have errant elevation values that are well above or below the surface. Statistical analysis will be performed on the elevation data which will include: minimum and maximum elevation, standard deviation and the total number of points within a given class range (i.e. two foot increments). Elevation values out of the norm, more than 20 feet from the next populous class will be flagged for review.

Quality Control of LiDAR Elevation Data in North Carolina



Discussion Summary

Date Discussed: 2/25/2005

Discussion Attendees: Thompson, Maune, Durham, Shelton, Wray

Summary of Discussion

Recommendations were adopted.

Final Guidelines

Guidelines follow the procedures discussed in the “Recommendations” section of this issue paper.

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