Remote Sensing Laser Survey and Imagery Technologies for Expediting Airport Mapping and Asset Management Applications

2014 FAA WORLDWIDE TECHNOLOGY TRANSFER CONFERENCE

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PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

ABSTRACT

This paper reviews the recently developed survey protocols and elevation accuracy specifications of LIght Detection And Ranging (LIDAR) sensors for airport obstruction mapping. Airborne LIDAR surveys have been reportedly conducted for over 24 airports in the United States. Due to daytime and nighttime operations and computational efficiency of LIDAR workflow obstruction mapping is expedited enhancing safety of aircraft and airport users. Additionally, LIDAR vector data can be re-analyzed to produce acceptable topographic mapping for engineering analysis of airfield assets. This significant improvement saves time and costs, compared to traditional field topographic surveying and aerial photogrammetry. The paper also presents applications of high spatial resolution aerial and satellite imagery for airport orthophotos and asset management applications. An example of three-dimensional feature extraction of airport infrastructure including air traffic control tower is presented. This is a cost-effective approach to enhance inventory of airport infrastructure assets.

INTRODUCTION

The crowded skies and increased use of satellite-based navigation systems are greatly impacting demand on the National Airspace System (NAS). The Federal Aviation Administration (FAA) regulates the NAS and airports to ensure aviation safety. The safety of the aircraft and airline passengers relies heavily on the safe and efficient use of airspace in the vicinity of an airport and enroute to the airport. This is accomplished by making sure no obstacles penetrate the obstruction-fee imaginary surfaces. Obstacles may include tree, cell towers, poles, construction cranes, wind turbines, transmission towers, other tall structures, and hilly terrain. An obstacle (including a mobile object) is an obstruction to air navigation if it is higher than any of the imaginary surfaces described in (a) Federal Aviation Regulations Part 77, (b) terminal instrument procedures (FAA Order 8260.3), or (c) other imaginary surfaces established by the FAA Airport Airspace Analysis System for vertically guided and non-vertically guided airports [1].

This paper presents the airborne laser surveying to expedite obstruction mapping with reference to the obstacle identification surface (OIS) and complementary use of high resolution aerial imagery. These efficient remote sensing data sources and geospatial technologies are easy to adapt for developing orthophotos and three dimensional models of airport infrastructure assets These remote sensing data applications enhance current practice of infrastructure inventory, geographical information system (GIS) mapping, and engineering analysis.

OBJECTIVES AND AIRBORNE LIDAR MAPPING NEEDS

The primary objective of this paper is to describe the validation of the airborne LIDAR technology for identifying and managing airspace obstructions as a cost-effective alternative to the traditional methods to prepare airport obstruction survey charts that meet government requirements. Further, geospatial application of complementary high resolution aerial imagery is presented to extract airport infrastructure features for asset management and engineering analysis.

The current NAS is made up of approximately 14,000 instrument flight procedures based on both conventional and satellite based navigational aids. The satellite-based procedures made up approximately 40% of the NAS a few years ago, but the FAA is continuously increasing this percentage to stay in line with the new technological advancements within the aviation industry including the implementation of the Next Generation (NextGen) Air Transportation System [2]. The obstruction chart surveys provide information critical to the safe and effecient operation of the NAS. The accuracy of these charts is paramount to the safety of each and every aviator.

AIRPORT OBSTRUCTION SURVEYS

The obstruction survey areas are defined by an airport-specific imaginary OIS, survey standards, airport design standards, and instrument procedures standards in the United States using the current applicable FAA Advisory Circular (AC) publication [3]. The primary goal of the FAA obstruction evaluation studies is to ensure the safety of air navigation from encroachments and the efficient utilization of navigable space by the aircraft. Local authorities or airport sponsors are responsible for regulating landuse in regard to structures that may penetrate navigable space. Obstruction surveys are directed and funded by the FAA at all obligated airports (airports receiving federal assistance) and by individual airport sponsors to satisfy a variety of airport data purposes. This information is used to:

- Providing geodetic control for engineering projects and airfield construction at airports including obstruction clearing, road building, and other airport improvement activities.
- Providing geodetic controls for navigational aid (NAVAID) site selection, and the air traffic control (ATC) tower location.
- Providing object/obstacle position and elevation data to FAA for design and development of instrument approach and departure procedures and other operational flight procedures.
- Determining whether obstacles are obstructions to air navigation and if it requires further study to determine aeronautical effect; such as adjustments to instrument approach minima, and/or obstruction marking and lighting.
- Certify airports for certain types of operations, including those conducted under Federal Aviation Regulations (FAR) Part 139 and FAR Part 77.
- Update official U.S. Government aeronautical publications.
- Providing obstacle data to airport users such as air carriers for use in operational planning including departure procedures and determining maximum takeoff weights for civil aircraft.
- Supporting airport sponsor height zoning enactment and enforcement. Determine maximum takeoff weights.
- Assist in airport planning and land use studies in the airport vicinity.
- Support miscellaneous activities, such as, aircraft accident investigations and special purpose one time projects.

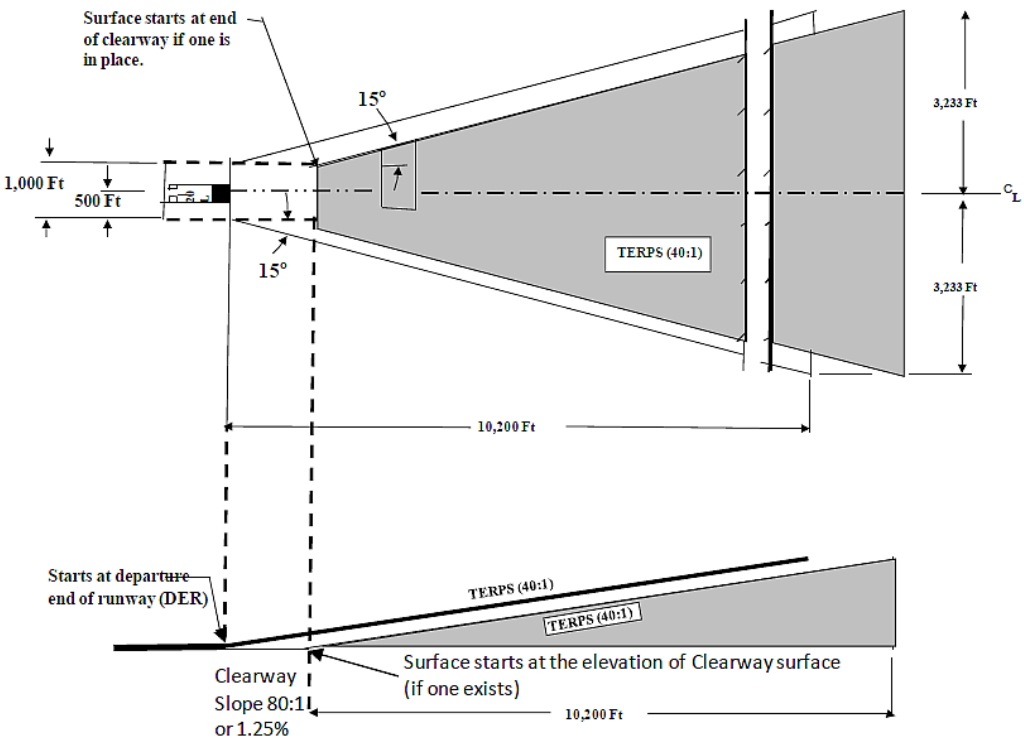

Figure 1. Departure surface.

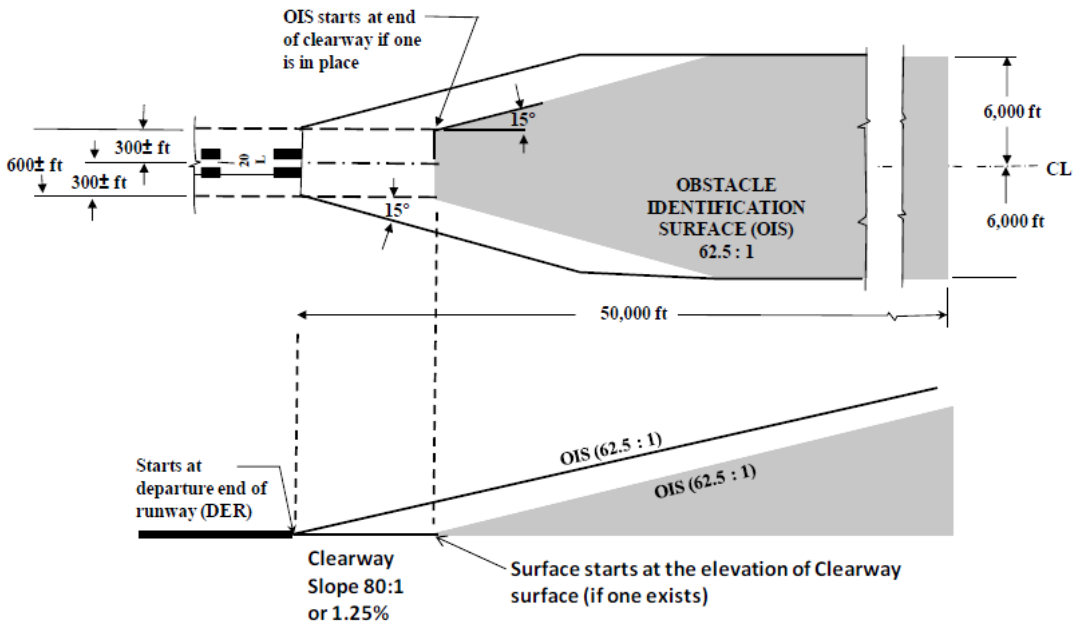

Figure 2. One-Engine Inoperative (OEI) Surface.

Figures 1 and 2 show two examples of departure OISs based on FAA AC 150/5300-18B [3]. These new surfaces greatly impact obstruction survey area requirements compared to the traditional Part 77 surfaces. Aircraft operators have the responsibility of considering obstacles and making necessary adjustments to their departure procedures to ensure safe clearance for

aircrafts. While satellite based navigation offers improved flexibility in the use of the nation's airspace, it also means greater demands for instrument approaches at airports which may not be able to serve the demand due to lack of conventional ground-based navigational aids. This new satellite-based navigation capability typically requires analysis of larger areas around airports and more precise data on objects and obstacles. A detailed summary of OIS surfaces and satellite based navigation flight procedures in presented by Uddin [4]. The GPS satellite navigation procedures are:

- Unaugmented GPS receivers
- Wide Area Augmentation System (WAAS), based on augmentation to GPS, provides a signal in space to support en route and precision/non-precision navigational approach.
- LNAV/VNAV (Lateral Navigation/Vertical Navigation) procedures for non-precision instrument approaches which use lateral guidance from GPS (556 m lateral limit) and vertical guidance from barometric altimeter or WAAS. The decision altitudes on these approaches are usually 107 m (350 ft) above the runway.
    - LPV (Localizer Performance with Vertical Guidance) is similar to LNAV/VNAV but more precise (40 m lateral limit). This enables descent of 61-76 m (200-250 ft) above the runway, and can only be flown with a WAAS receiver.
    - If the WAAS service becomes unavailable, all GPS or WAAS equipped aircraft could revert to the LNAV decision altitude and land safely using GPS only.

The Localized Performance (LP) procedure uses the high precision of LPV for lateral guidance and barometric altimeter for vertical guidance. These approaches are needed at runways where due to obstacles or other infrastructure limitations, a vertically guided approach (LPV or LNAV/VNAV) cannot be published. LP approaches can only be flown by aircraft equipped with WAAS receivers. The minimum descent altitude for the LP approach is expected to be approximately 300 ft above the runway. LPV Approaches are operationally equivalent to the legacy Instrument Landing System (ILS) equipment but are more economical because no ILS navigation equipment has to be installed at the runway. With many GA airports having no ILS, this near-precision approach provides added safety of vertical guidance. It is also a high benefit-cost ratio, considering the cost of a typical ILS installation to just one runway end can be more than a million dollars. Not many general aviation airports are eligible or can afford such an expense. According to the Aircraft Owners and Pilots Association (AOPA) there are 5,400 public-use airports in the United States, with 15,500 runway ends. Only 4,686 of these runway ends have instrument approaches of any sort, leaving about 11,000 runway ends available only in visual conditions [5].

The current FAA AC 150/5300-16A standards for Airport-GIS (A-GIS) and surveying program [6] include Airport Airspace Analysis (AAA) surveys and topographic surveys. The survey data are used to publish electronic ALP or eALP that staisfies the Amendment 33 to ICAO Annex 15 requirements for electronic sets of Terrain and Obstacle Data (eTOD). The airport surveys in the U.S. use three airport specific geodetic controls: one Primary Airport Control Station (PACS) and two Secondary Airport Control Stations (SACS). The current FAA survey AC 150/5300-17C standards [7] apply to any remote sensing surveying including airborne LIDAR surveys. Uddin, et al [8] describe a workflow chart for airport surveys to meet the FAA specifications of A-GIS and eALP.

For over 60 years the National Geodetic Survey (NGS) provided the obstruction surveys and aeronautical charts using high resolution photogrammetry. It is important to have survey data verification if third party surveys area used. Figure 3 shows examples of the results of the NGS verification and quality checks of obstructions and comparison with the data/imagery provided by a commercial survey provider. The NGS imagery was acquired at 12,000 ft (3,658 m) above ground level. The NGS review process shows several obstructions missed in the contractor's obstruction maps, as well as NGS identification of mobile crane that was missed by the survey provider [4]. This example clearly shows the importance of independent obstruction survey data verification for producing accurate obstruction identification charts. The current AC 150/5300-18B does not provide specific details for independent validation and verification procedures, as well as no detailed protocols for NGS quality review check. Therefore, it is necessary to establish an outline of NGS verification and quality review process as recommended by Uddin [4].

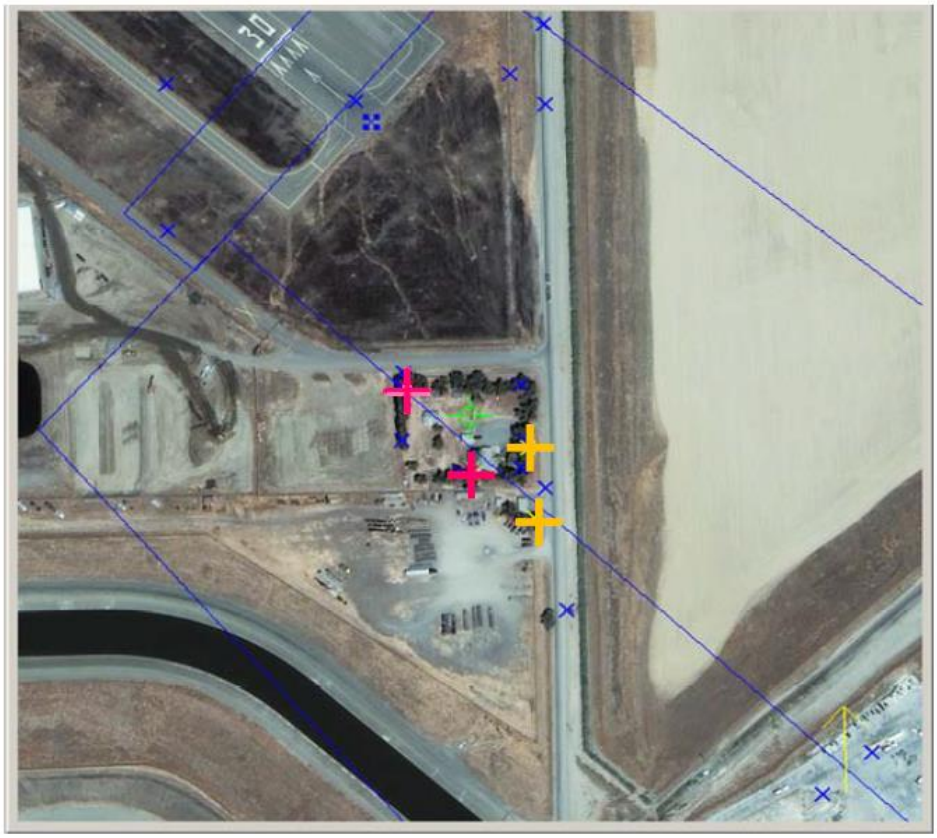

Figure 3. NGS Quality Checks of Obstruction Survey using Aerial Imagery.

(credit: Chris Parrish, NGS, 2009; used with permission [4])

AIRBORNE LIDAR FOR AIRPORT OBSTRUCTION MAPPING SURVEYS

As stated in the preceding section, the obstruction mapping information has traditionally been obtained with aerial imagery and conventional surveying techniques, but obtaining accurate topography data, as well as obstruction identification, requires extensive on-the-ground data collection. New aerial sensors have been developed that have better spatial and spectral

resolutions than traditional aerial photography. Advances in computer hardware/software have created opportunities for improving the accuracy and efficiency of automated digital terrain models. Three-dimensional digital coordinate data are directly loaded into terrain mapping, GIS, and other computer-aided design (CAD) software. This leads to efficient and error free data processing and map generation. LIDAR systems directly acquire height information from both the ground and canopy top, simultaneously, and could provide a detailed picture of the three dimensional characteristics of the area surrounding the aerodrome. The capabilities of the LIDAR systems have been proven to provide automated, accurate ground digital terrain models, and digital canopy replication, even in densely vegetated areas of all terrain types. The LIDAR data has been found to be invaluable in many areas, especially where traditional methods would not be able to penetrate the canopy, or would be cost prohibitive. For example, LIDAR has been shown to provide points within a +/- 15-cm RMSE, which is the accepted NMAS for 1-ft interval contour mapping [9].

Airborne LIDAR survey for obstruction mapping was studied and validated by NGS in several different studies conducted in 2001, 2002, 2003, and 2006 using LIDAR sensors with pule repetitive frequency (PRF) of 33, 50, 50, and 70 kHz, as shown in Table 1 [4]. In Phase I study only 94% obstacle objects were identified; however after optimizing data collection protocols, 100% of the field-surveyed obstruction objects were successfully detected. Phases II and III studies showed 100 % detection of obstructions at both airports. A wide variety of objects were surveyed ranging from trees to light poles and buildings. The dual LIDAR approach resulted in a 100% detection rate of the field-surveyed obstructions at both airports. The vertical accuracy RMSE was also quite good for both airports: 1.12 m for Stafford and 0.69 m for Frederick. Figure 4 shows an example of overlaying the obstruction identification surfaces on the LIDAR-derived digital surface model (DSM) to facilitate obstruction identification [10].

Table 1.
NGS airborne LIDAR research studies, 2001-2006

Year	Project	Study Site	Optech's model	LIDAR Specifications	
				PRF	Degrees from azimuth
2001	Phase I	Gainesville Regional Airport, Florida	ALTM 2033 and ALTM 2010	33 kHz	Nadir only
2002	Phase II	Gainesville Regional Airport, Florida	ALTM 2050	50 kHz	Nadir plus up to 40 degrees forward looking
2003	Phase III	Stafford Regional Airport, Virginia	ALTM 2050	50 kHz	Nadir plus 20 degrees forward looking
2003	Phase III	Frederick Municipal Airport, Maryland	ALTM 2050	50 kHz	Nadir plus 20 degrees forward looking
2006	Phase IV	University of Wisconsin, Madison	ALTM 3100 & wave form digitizer	70 kHz	Nadir only

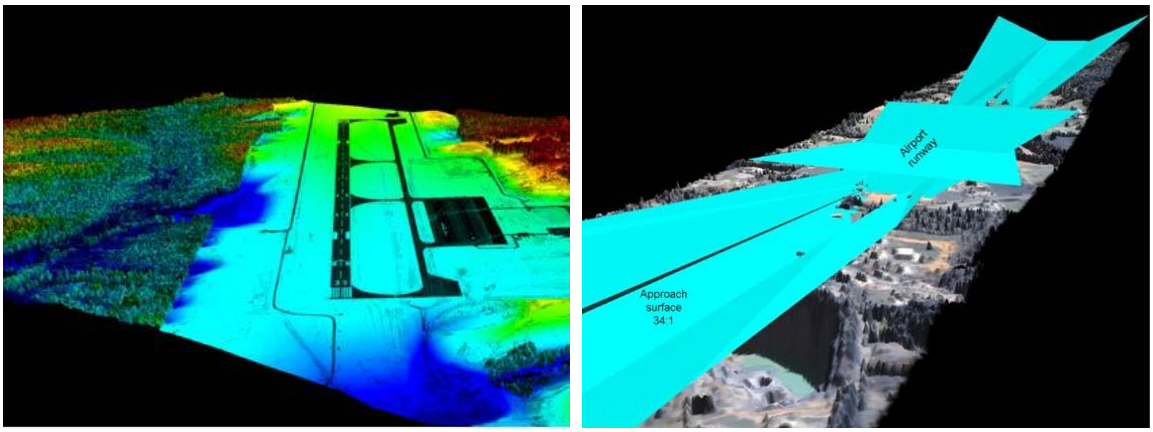

Figure 4. LIDAR Coverage (left) and Obstructions Through OIS (right) Investigated by NGS. (credit: Chris Parrish, NGS, 2009; used with permission [4, 10])

In an independent study, the Ohio University Avionics Engineering Center researchers used an airborne Riegl LMS laser scanner with an average 10 kHz PRF which was flown on January 15, 2005 at Braxton County Airport. The results showed excellent positional accuracy (3 to 4 m horizontal and 2.6 m vertical) at 95% confidence from the data collected during eight approaches to Runway 19 [11]. This measured accuracy of LIDAR data was better than the accuracy requirements for a CAT IIIb LAAS approach (5.0 m horizontal and 2.9 m vertical 95% of the time).

General procedures to collect airborne LIDAR data for surveying terrain topography, commonly called Airborne Laser Mapping, and airport obstruction mapping are described in detail by Uddin [4, 8]. Scanning areas with elevated objects may result in “blank areas” or missing data behind the objects. For obstruction measurements, the first return and all other returns are used. After the field data collection process is completed, the data points (already in the digital format) can be easily uploaded to computer workstations for processing and interpretation. The processed LIDAR data can be imported into GIS as thematic color maps of elevation and contours, used to create planimetric features, overlaid on the raster imagery for obstruction locations and airport layout plan, and used for other engineering applications, thereby supporting multiple uses through a single data collection. Except for compliance with avionics regulations, there are no other operating constraints, such as cloud and vegetation cover, traffic and usage, and time of day. Conventional topographic surveys are slow and aerial photogrammetry is limited by daytime operating constraints and time consuming data processing and interpretation. More benefits of LIDAR vs. photogrammetry are compared by Uddin and Willis [12].

To see from the air the extremely small cross section of these types of objects is a difficult problem for all remote sensing methods including LIDAR and photogrammetry. A key technical concern in using LIDAR for airport obstruction surveying is achieving sufficient ground point density and received signal strength to detect small-diameter, low-reflectance objects. The NGS research provided an unbiased scientific assessment of LIDAR accuracy to detect and measure all types of obstructions. The NGS recommendations in published papers are being followed

already by commercial LIDAR survey contractors in their airport obstruction survey workflows [4]. The desired accuracy level is obtained with planned point spacing and point density over the mapped area. The ground footprint and ground point density of LIDAR can be calculated from flight planning parameters [4] and listed as follows: the pulse repetition frequency PRF in kHz, ν the aircraft ground speed in m/s, the LIDAR scanned swath width SW in m, and the aircraft altitude above ground level in m. Detailed equations for point density based on PRF and flightline planning (both longitudinal and transverse tracks) are listed in ACRP Digest [13] and discussed by Uddin and Willis [12].

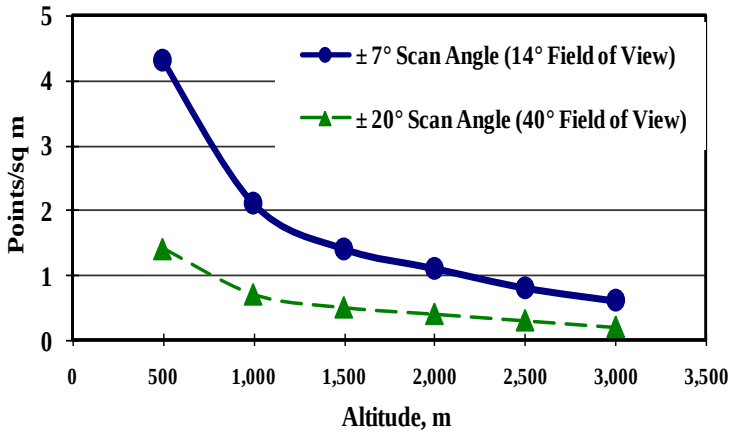

Figure 5. LIDAR Points Density vs. Flying Altitude for the Assumed Sensor Data.

Figure 5 shows typical variations of point density with respect to increasing flight altitude at 125 knots aircraft speed. The data represents a nadir-looking LIDAR setting of 33 kHz PRF and a 7° or 20° scan angle. For example, 4.3 points per sq m spatial point density is expected at 500 m altitude and 7° scan angle. By varying the aircraft altitude, aircraft speed, scan angle, and scanner frequency, the operator is able to program ground point spacing and density to fit the particular survey mission (Figure 6). Current LIDAR sensor systems operating at 100 or higher kHz PRF can achieve up to 30 points per sq m spatial point density. With the desired density and accuracy of the resultant digital terrain model and obstruction identification, coupled with a schedule that expedites the timeline compared to the previously mentioned conventional methods for these constraints, LIDAR provides an excellent avenue for technical and economic advantages in aviation obstruction mapping and airport asset management applications.

The Airport Cooperative Research Program (ACRP) project 03-01 evaluated the accuracy and costs of LIDAR in comparison with conventional surveying methods for airport obstruction chart surveys [4, 13]. Figure 6 shows flightlines over LIDAR intensity image for Anoka-County-Blaine Airport obstruction survey project in Minnesota. Figure 7 shows the results of obstruction measurements and verification through photogrammetry by a commercial survey provider [14]. The data was collected using a LIDAR system PRF of 70 kHz for a Nadir flight plan and 20° forward-looking flightlines (as recommended in NGS studies). Aerial imagery was collected at the time of obstruction survey to assist in attributing obstructions and in distinguishing real features from false returns, such as aircraft or birds.

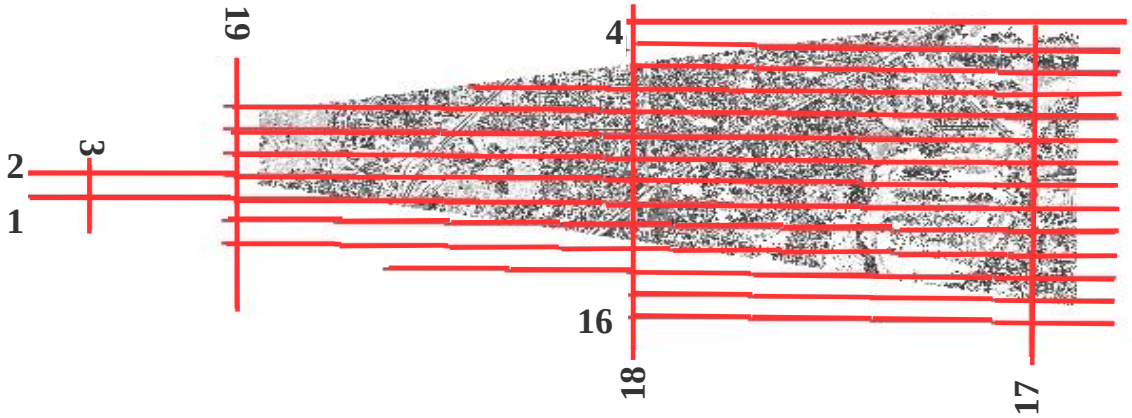

Figure 6. Flightlines Over LIDAR Intensity Image, Anoka-County-Blaine Airport, MN [4].

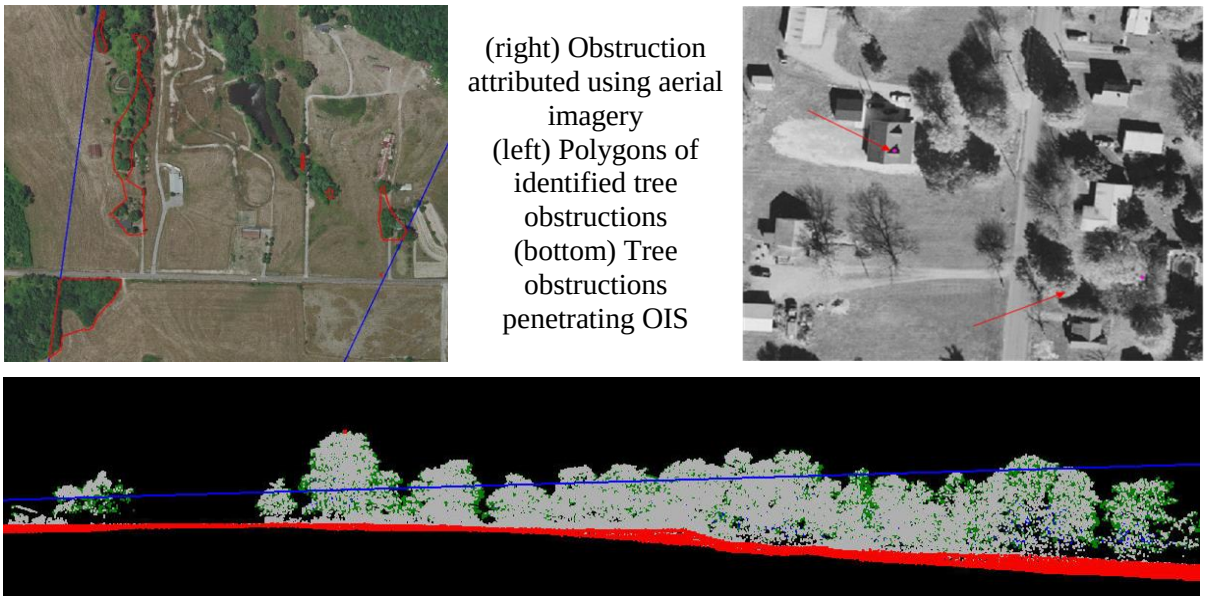

Figure 7. Results of obstruction analysis [4, 14]. (credit: Optimal Geomatics)

Results of the ACRP03-01 project team's research indicate a total of 28 airports where LIDAR surveys have been done for airfield and obstruction mapping [4, 13]. A GIS spatial map of the geographical locations of each of the airports is shown in Figure 8. The map includes the three airports used for NGS studies and Vancouver Airport in British Columbia, Canada where LIDAR surveys were reported. At least 24 other airports have been surveyed using airborne LIDAR including the University Ohio research study (Braxton County Airport) and others by commercial survey contractors. At least one commercial LIDAR survey was funded by the FAA for William R. Fairchild International Airport at Port Angeles, Washington. Most other commercial LIDAR surveys were funded and authorized by airport agencies probably as a part of AIP state block grants. The largest group is general aviation, non-hub is the middle group, and

small hub is the smallest. The largest number of enplanements was at Jackson-Evers International Airport (JAN) in Jackson, MS. This airport had 717,576 enplanements and is considered a small hub. The smallest number of enplanements shown on this chart is Andrews Air Force Base (ADW) in Washington, DC, which had 2,753 enplanements.

The reviewed list of previous LIDAR surveys (Figure 8) includes several airports in the FAA's Southern Region area of responsibility. This region has been quite progressive on automation and innovative projects. However, most of the surveys were conducted at general aviation airports, and most of the states in that region are "Block Grant" states, meaning the state administers the grant, including project formulation in cooperation with the sponsor, through bidding, award, and construction. The team was not able to get project information within the project time constraint for all airports from the state aviation agencies. Cost data from only seven airports were available from publicly available information.

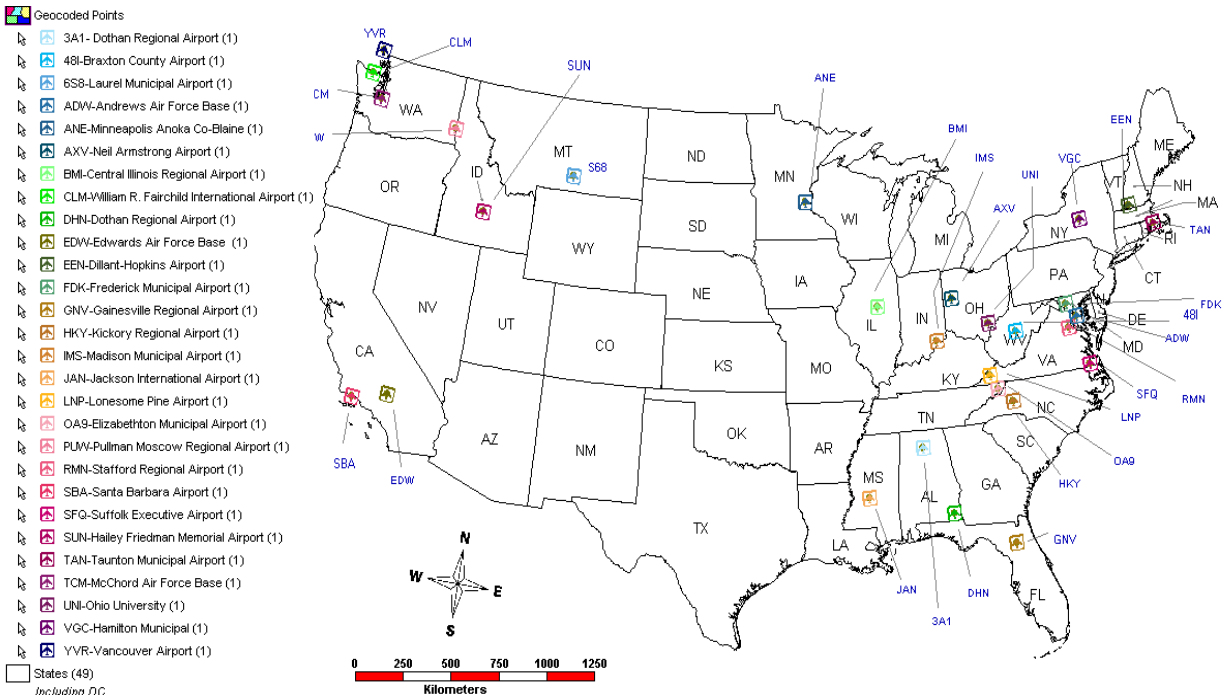

Figure 8. Spatial Distribution of Airports with LIDAR Obstruction Survey History.

Based on the airport survey data from these cases, LIDAR obstruction surveys are cost-competitive with complementary use of aerial photo and photogrammetry at about $3,000 to $4,000 per km^2 for an area ranging from 4 to 24 km^2 compared to the traditional photogrammetry only. Traditional photogrammetry cost varies from $4,000 to $14,000 per km^2 based on a long history of use. The cost variation depends upon weather related flight constraints, premark setup and ground control data, dense vegetation and shadows, and terrain. Greater survey area will reduce the overall cost per km^2 of both LIDAR and photogrammetry.

The ACRP03-01 project [13] also documents the recommended LIDAR surveying protocols and accuracy specifications for airport obstruction mapping. The study also reviewed several commercial LIDAR data processing software packages [4]. The LIDAR technology is a cost-effective tool for creating high resolution digital terrain models and contours [12]. LIDAR data are complemented by the conventional aerial imagery that provides orthophotos of the airport area of interest (AOI). A LIDAR survey provides millions of georeferenced 3D points over the entire survey area, compared to the extraction of elevation and features on discreet locations by stereoscopic photogrammetry. Additionally, LIDAR vector data can be re-analyzed to produce acceptable topographic mapping for engineering analysis of airfield assets. This significant improvement saves time and costs, compared to traditional field topographic surveying and photogrammetry. The LIDAR terrain data and contours provide dense point spacing for more accurate drainage design, detailed earthwork quantities, and infrastructure construction costs [15].

ADVANCES IN LIDAR TECHNOLOGY FOR AIRPORT SURVEYING

An advanced development in the field of airborne LIDAR is full-waveform LIDAR systems employing a small-footprint. The NGS investigated automated extraction and classification of airport obstructions in full-waveform LIDAR data collected over Madison, Wisconsin (Table 1) using a 3D wavelet-based approach [4]. The full-waveform LIDAR processing methodology developed and implemented in this NGS study is described by Parrish [16]. The point clouds generated from the full-waveform data using the algorithms contain an average of 252% more points on vertical objects of interest than the point clouds generated from the discrete-return data using the manufacturer's software. All identified obstructions and their heights, penetrating a simulated imaginary surface, were shown on the aerial imagery of the study site in the format required by the FAA, not presented here for brevity.

A summary of LIDAR industry survey of 10 different systems above 70 kHz PRF indicates:

- Maximum PRF of above 150 kHz to 500 kHz for nine of the reviewed systems.
- Maximum point density in a single pass ranging 11 to 18 per m^2 for these nine systems. (Assuming 75 m/s aircraft speed, ±20˚ scan angle, 70Hz scan rate, 500m (~5000ft) flying height above ground level, and maximum system PRF setting used in calculation)

Many current LIDAR sensor systems operate 100 kHz or higher PRF, thus enabling these with appropriate flight mission parameters and overlapping flightlines to achieve denser point spacing up to 30 points per m^2. This advance data collection capability will enhance the detection of thin tall objects, constructed structures, and natural terrain.

3D FEATURE EXTRACTION FOR AIRPORT INFRASTRUCTURE ASSETS

Airport assets can be visualized in a GIS map as planimetric features using georeferenced aerial imagery and orthophoto for producing eALP. The planimetrics can be further used to create built and non-built surface type map and surface temperature map to estimate heat-island effects and sustainability dimensions. An example of an airport application is described by Uddin [15]. However, the visualization of infrastructure inventory for asset management can be greatly enhanced by geospatial mapping of 3D features. This has been accomplished using

GeoGenesis™ photogrammetric software suite, which was developed in support of the US Navy [17]. This software is designed to exploit stereo aerial photo and high resolution satellite imagery with the digital elevation model data, as well as LIDAR data. It allows the user to easily extract accurate 3D features for use in a variety of engineering applications, which include airport obstruction surveys. The mathematical processes are those by which geometric properties of objects are determined from imagery. These may include orthorectification, multi-resolution fusion, and mosaicking. After registering the data, features are extracted using the FeatureXTract™ module within the software. The process is easy to learn and takes less than an hour to extract terminal buildings, a control tower, and two runways.

A case study involved extracting 3D features over the airport in Louisville, Kentucky using overlapping aerial imagery. The selected features were extracted using a split screen interface and intuitive extraction tools. The software acquires height information of constructed and natural features through an easy-to-use stereo-analysis of stereo pair of high resolution aerial or satellite imageries. Therefore, it can be used to produce 3D models of transportation and urban infrastructure rapidly and at a significantly lower cost. The generated features may be exported to a variety of formats including the ESRI Shapefile format for further exploitation in standard GIS tools. The software allows the user to export to OpenFlight and GoogleEarth KML and KMZ formats for additional visualization applications. Figure 9 shows an example of the resulting features of Louisville Airport in GoogleEarth [18].

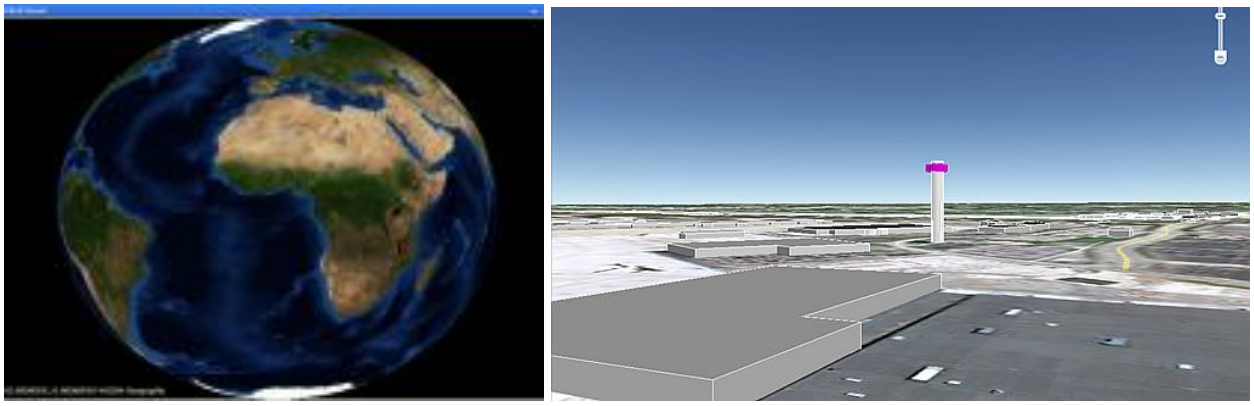

Figure 9. Extracted 3D Features at the selected Airport [9].

CONCLUSIONS

The ACRP03-01project explored the readiness of LIDAR technology as a cost-effective alternative to the traditional methods for collecting the data required to prepare airport obstruction surveys that meet government requirements. Airborne LIDAR surveys have been reportedly conducted for over 24 airports in the United States. Due to daytime and nighttime operations and computational efficiency of LIDAR workflow obstruction mapping is expedited that will enhance safety of aircraft and airport users. Airborne LIDAR surveying protocols and accuracy specifications have been published specifically for mapping airport obstructions.

Airborne LIDAR survey technology is a computationally efficient digital mapping method for civil and environmental applications. The richness and potential applications of LIDAR data

for airport mapping and asset inventory will lead the GIS and CAD communities rapidly into the 3D geospatial world. A raster aerial imagery can be used to produce accurate spatial planimetrics of airfield infrastructure assets and develop GIS maps as required by the current FAA standards. This is a cost-effective approach to estimate built surfaces, assess heat-island effects, and measure sustainability dimensions. An example of 3D feature extraction of airport infrastructure including air traffic control tower is presented using a specialized geospatial software that uses a stereo pair of raster aerial imagery.

ACKNOWLEDGEMENT

The author appreciates the support of the following collaborators: Christopher Parrish (National Geodetic Survey), Bill Gutelius (Active Imaging System), David Ward, Eric Lester of the IAVO Research and Scientific, and Optimal Geomatics. Thanks are due to Colby Willis, Katehrine Osborne, and several graduate students who contributed to the ACRP03-01 project. The contents of this paper reflect the views of the author who is responsible for the facts, findings and data presented herein.

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