"Research-Quality" Airborne Laser Swath Mapping:
The Defining Factors

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I. Introduction

Airborne Laser Swath Mapping (ALSM), also known as airborne lidar, is no longer an exotic mapping technique restricted to the domain of the most technologically advanced government agencies such as NASA or DOD. The leading commercial manufacturer of ALSM systems recently announced the sales of its one-hundredth system—more than one-half of which were sold to commercial companies, government agencies, and academic institutions outside of the United States. Anyone with one to two million dollars can purchase the essential instrumentation and computer software to collect and process ALSM observations. But, those who operate an ALSM system in a "black box" mode will obtain data of widely varying quality, and even worse, will generally have no way of knowing the quality of the observations they collect, or of the products derived from those observations.

1.1 Brief Historical Background

By the 1980s, NASA was experimenting with airborne laser altimetry systems for such applications as mapping terrain, measuring sea surface height, and monitoring changes in the Greenland ice sheets [Krabill, *et al.*, 1984]. While variations on the basic lidar design, such as large-footprint full-waveform systems, have appeared, it is the small-footprint, multiple discrete-return form that has become the most widely used for solid earth sensing because of the higher resolution spatial sampling it offers. During the late 1990s, such ALSM systems became available from commercial manufacturers that were compact, lightweight, and power efficient enough to be operated from a light single-engine aircraft. Earth scientists quickly recognized the potential benefits of ALSM observations for their research, but the cost of the systems and the technical expertise required to operate them were formidable.

In 2003, the National Science Foundation (NSF), responding to the demand for these data from the scientific community, approved a proposal submitted by the University of Florida (UF) and the University of California at Berkeley (UCB) to establish the National Center for Airborne Laser Mapping (NCALM). The primary mission of NCALM is to collect *research-quality* ALSM observations optimized for scientific projects approved and funded by NSF. During the past four years, NCALM has collected ALSM observations for more than 50 NSF funded research projects across the nation.

1.2 Purpose of This White Paper

In this white paper we will describe current instrumentation, calibration and data collection procedures, as well as the reduction, processing, filtering, analysis and interpretation of ALSM observations that are essential to producing *research quality*[1] data sets. "Research-quality" is not a term that implies a particular spatial sampling or processing algorithm since the scientific value of the data ultimately depends on all aspects of the collection and reduction procedures and the degree to which those procedures are openly shared with the scientific community. Thus, equally important is the documentation required to accurately gauge the quality, as well as deficiencies or limitations, of the final products. It is critically important for users of ALSM data to know the limitations of the data, so that they do not interpret artifacts as information about their scientific applications.

This white paper contains quantitative information on the performance specifications of available ALSM systems, on data collection procedures with those systems, and on the processing and filtering of the data to extract information useful to researchers working on subjects related to plate deformation and faulting, surface erosion, storm damage, land slides, snow and ice pack accumulation and melting, forestry, evolution of salt marshes, and others. But, the reader must recognize that virtually every facet of ALSM technology (including both the hardware and processing algorithms) is changing rapidly, and even as this white paper was being prepared, companies, government agencies, and academic institutions around the world were working on improvements that could make this quantitative information contained herein quickly out-of-date. For example, our own research team at UF is currently developing an ALSM unit that collects a 10×10 array of surface points from each laser shot. While the laser has a repetition rate of only 8,000 pulses per second (pps), the spatial resolution is equivalent to a single channel unit with a laser rate of 800,000 pps. When this or similar systems become operational, they will provide contiguous coverage of the terrain with decimeter spatial resolution in a single pass, and some of the particular specifications of research quality data will necessarily be updated.

Academic institutions, such as UF and UC Berkeley, are naturally oriented to always seek out and advance the state of the art. We therefore view this white paper as a living

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[1] We use the terminology "research quality" or "research grade" to describe lidar data collection and reduction procedures that meet the high (and evolving) standards of the scientific research community necessitated by their applications of lidar data.

document that will require updating over time. While the particular specifications, such as laser pulse rates, will evolve, we believe the philosophy behind *research quality* ALSM lidar data collection and reduction will stand firm as the desired standard to be met.

II. Sensor Technology

2.1 Laser Pulse Rate — Spatial Resolution

Throughout the history of astronomy scientists have sought larger and larger aperture telescopes. The motivation is simple: larger aperture telescopes enable them to collect more light and thus to look deeper into space to discover new objects. And the information collected by the ever improving observations has revealed a universe with scale, complexity and age beyond the imagination of all previous generations of astronomers.

As important as the telescope collecting area is considered in astronomy, so also is the importance of the laser pulse rate in ALSM mapping. The reason for this is simple: a higher pulse rate implies closer spacing of the laser footprints on the terrain and subsequently better spatial resolution for the Digital Elevation Models (DEMs). Better spatial resolution enables users to view and quantify smaller surface features more precisely, helping them to identify and understand the processes by which they were formed. For the small footprint single-channel design used in virtually all current commercially manufactured ALSM units, the higher the laser rate, the better the surface spatial resolution achieved in a single pass over an area. For that reason alone manufacturers have given high priority to increasing the laser pulse rate, improving from 5 or 10 kHz a decade ago to 100 to 150 kHz (or even more) today.

The original Optech unit purchased by UF operated at a laser pulse rate of only 5 kHz. It was upgraded to 10 kHz and then to 33 kHz, just in time for the initial NCALM projects. When a higher spatial resolution was required for a specific application, the only options were to fly multiple passes over the area and/or to fly lower and slower with narrow scans. Combining data collected in multiple passes generally resulted in some degradation of accuracy achieved for the surface coordinates because of errors in the aircraft trajectories that had to be combined into a single data set. The final quality of ALSM data is not set solely by the laser pulse rate, but other factors being equal, the higher the pulse rate the better, and that was certainly one of the driving

factors that led UF researchers in February 2007 to purchase a new 167 kHz Optech Gemini system.

Staying abreast of significant advances in the instrumentation is essential to producing research quality ALSM data, and increasing the laser pulse rate by a factor of 4 to 5 is clearly significant by any definition. In fact, an increase in pulse rate of that magnitude represents the development of a new generation instrument. It must be given heavy weight in evaluating the expected information content of the ALSM data collected, and therefore in itself changes the particulars of the definition of research quality ALSM data.

Table 1 lists the manufacturer's performance specifications for the Gemini system, now the primary instrument used by NCALM. The most notable advances of the Optech Gemini over the Optech 1233 system previously used by NCALM are (1) up to ×5 faster laser pulse rate, (2) four returns per shot instead of just two, (3) choice of narrow or. wide angle beam divergence, and (4) newer inertial measurement unit (IMU) with faster sampling of the aircraft's orientation.

Table 1: Optech Gemini system specifications. AGL refers to Above Ground Level.

Specifications			
Serial numbers	Sensor Head 06SEN195 Control Rack 06CON195		
Operating altitude	150 – 4000 m nominal		
General Enhanced Accuracy Specifications	Laser Repetition Rate	Horizontal Accuracy (m 1 σ)	Vertical Accuracy (m 1 σ) AGL
	33 kHz - 50 kHz	1/5500 x altitude	< 5 cm up to 500 m < 10 cm up to 1 km < 15 cm up to 2 km < 20 cm up to 3 km < 25 cm up to 4 km
	70 kHz	1/5500 x altitude	< 5 cm up to 500 m < 10 cm up to 1 km < 15 cm up to 2 km
	100 kHz	1/5500 x altitude	< 10 cm up to 500 m < 15 cm up to 1 km < 20 cm up to 2 km
	125 kHz	1/5500 x altitude	< 10 cm up to 500 m < 15 cm up to 1km
	143 kHz	1/5500 x altitude	< 15 cm up to 500 m < 20 cm up to 1 km
	167 kHz	1/5500 x altitude	< 35 cm @ 750 m
Range capture	Up to 4 range measurements for each pulse including last		
Intensity capture	12 bit dynamic range for each measurement		
Scan frequency	Variable; maximum 100 Hz		
Scan angle	Variable from 0 to ± 25°, in increments of ±1º		
Scanner Product	Scan Angle x Scan Frequency ≤ 1000		
Roll compensation	5 Hz update rate (Scan angle + Roll Comp. Angle = FOV, i.e. ± 25º allows ± 5º compensation)		
Swath width	Variable; 0 to 0.93 x altitude m		
Position Orientation System	Applanix – Optech custom POS including internal 12 channel dual frequency 10 Hz GPS receiver		
Laser repetition rate	33 kHz (maximum AGL 4.0 km) 50 kHz (maximum AGL 3.0 km) 70 kHz (maximum AGL 2.5 km) 100 kHz (maximum AGL 2.0 km) 125 kHz (maximum AGL 1.6 km) 142 kHz (maximum AGL 1.4 km) 166 kHz (maximum AGL 1.2 km)		
Data storage hard drive	Ruggedized removable hard drive, (10hr continuous log time @ 100 KHz)		
Beam divergence	Dual 0.3 mrad (1/e) and 0.8 mrad (1/e) *; 0.16 mrad optional		
Eye safe range	*See eye safety table*		
Laser classification	Class IV (FDA CFR 21)		
Power requirements	28 V (continuous), 45 A (maximum)		
Operating temperature	Control rack: 10 to 35º C Sensor head: -10 to 35º C (assuming the use of thermal jacket)		
Storage Temperature	Control Rack: – 10 º to 50º C Sensor Head: 0 º to 50º C		
Humidity	0 – 95% non-condensing		
Control Rack Measurements	653mm x 591mm x 485mm, 55kg		
Sensor Head Measurements	298mm x 249mm x 437mm, 23kg		

* Operational altitude calculated depending on eye safe table.

2.2 Intensity Observations

It is absolutely essential that ALSM systems using the high signal-to-noise design currently favored by manufacturers record the strength or "intensity" of the return signals, and that the instrumentation includes features such as different channels for strong and weak signals and constant fraction discriminators in the range measuring circuitry. Most commercial lidar units operate at laser wavelengths in the near-IR spectrum[2] and employ avalanche photodiodes (APDs) to detect the returned laser light. Because the terrain and landcover consist of objects that range from minimally reflective to highly reflective in the near-IR the dynamic range of the return signal can exceed three orders of magnitude. Most APDs are not capable of a linear response over so large a range. As a result, systems that merely claim to have "automatic gain control" generally suffer significant range walk as a function of signal strength, which is when bright returns produce a reduction in the perceived range to the object. Range walk can be detected by artifacts in the final set of points. The most obvious artifacts include paint stripes that appear to float above highway surfaces because of their high reflectivity, but there are more subtle artifacts, such as a vertical offsets at the intersections of wet and dry sand on beaches and where mineral content in flat desert playas and alluvial fans changes. Optech supplies lab-calibrated intensity lookup tables with each ALSM unit to eliminate range walk, and NCALM works with Optech to refine our calibration tables as needed.

An ancillary measurement that can often add value to the lidar data is the simultaneous collection of aerial digital photography. While coincident aerial photography is not strictly required to produce research quality ALSM data, it can be useful to locate precisely the changes in spectral properties of the surface and the presence of short vegetation that can in turn help researchers interpret the lidar elevations and intensities. NCALM collects sub-meter resolution digital aerial photography in the visible and near-IR bands as needed to support ALSM data collections for these reasons.

2.3 Number of Returns Per Shot

Many of the transmitted laser pulses encounter surfaces that cover some fraction of the laser footprint before the remainder of the pulse reaches ground level. Examples of such surfaces include electrical wires, poles, birds, trees, brush, and roof edges. In thickly wooded areas

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[2] The most commonly used lasers in modern ALSM systems are Nd:YAG lasers, which have an operating wavelength of 1064 nanometers.

virtually no pulses may make it to ground level without first encountering partial reflecting surfaces that return enough light to trigger the range circuit. If a system records only one return per shot, it will produce sparse returns from the ground in vegetated areas that are not appropriate for research applications. If the system records only two returns per shot, they should be the first and last—again to maximize the number of returns from the ground surface. Most systems now record three, four, or more pulses per shot, and this is particularly important for researchers who need to have truly three dimensional point clouds for such applications as forestry and ecology.

Two parameters govern the extent to which multiple reflections along the laser beam's path can be resolved. The first is the beam divergence. Most ALSM systems employ a relatively narrow beam divergence of just a few tenths of a milliradian. Newer systems, such as that used by NCALM, can provide a switchable divergence, for example from 0.3 milliradians to 0.8 milliradians. Which beam divergence is best depends on the structure and spatial distribution of the landcover. Having the capability of more than one divergence provides a valuable flexibility to optimize the data collection for bare-surface detection in a variety of circumstances. The other parameter is known as the "dead time". This refers to the time required after a return is registered for the receiver and data capture circuitry to return to a state where it can register a subsequent return from that same laser pulse. The result is a "blind zone" distance below an object that generates a return signal. Over this distance no other objects can be detected (see Figure 1). Dead time is primarily determined by the transmitted pulse length, but is also affected by pulse shape, detector design, and the receiver circuitry.

ALSM laser

1st return (e.g. a tree canopy)

$c\tau$ governs the length of the blind zone for a given detector response time. Typically it is almost 3 meters.

Object height above the ground

next return (e.g. the ground)

Ground
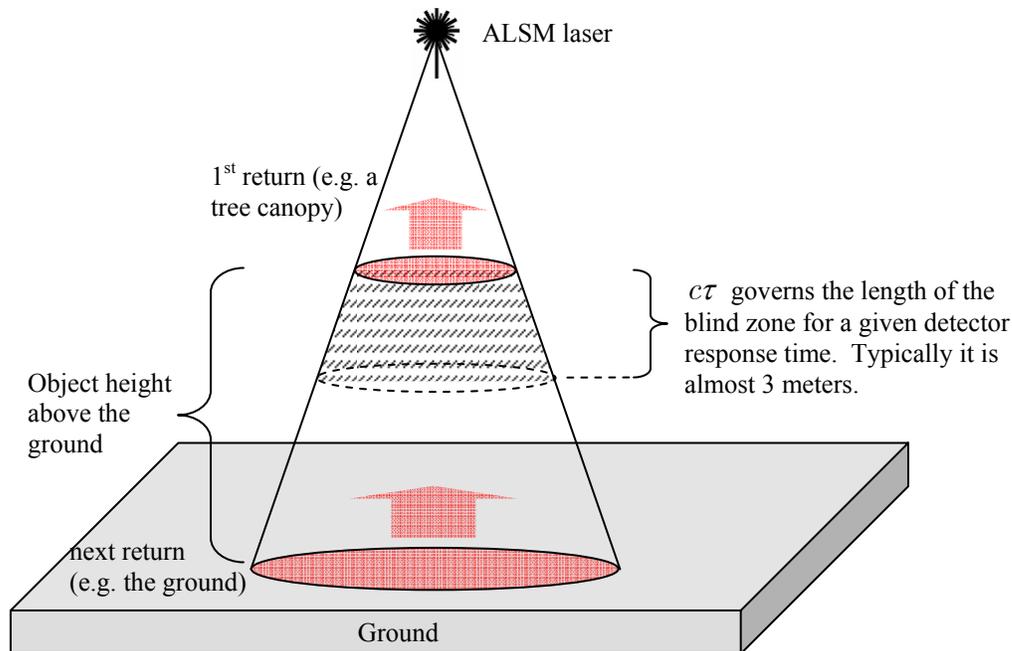
Figure 1: The "blind zone" effect (not drawn to scale). All ALSM detectors have a finite response time, which implies a blind zone for single-channel systems after a return is registered. The blind zone extent is determined largely by the light propagation speed c times the pulse length τ. The effect precludes the recording of a subsequent return from any object significantly less than $c\tau$ meters below the previous return on a given shot. For a 10 nanosecond pulse length and a single-channel APD, the blind distance would be almost 3m. This limitation can be ameliorated, however, using narrow beam divergence and high laser pulse rates to get more first returns to reach the ground.

An alternate approach to recording discrete return "events" for each shot is to use a wave form digitizer to capture the instantaneous strength of the return signal at closely spaced regular intervals. The NASA sensors Laser Vegetation Imaging Sensor (LVIS) and Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) employ waveform digitization over very wide beams (footprints of tens of meters) to study vegetation canopies. However, such large footprints are not suited to mapping topography at high horizontal spatial resolution. More recently, the NASA Experimental Advanced Airborne Research Lidar (EAARL) sensor and Optech have demonstrated waveform digitization with small footprint ALSM. However, waveform digitization typically increases the data that must be recorded by orders of magnitude, and, more importantly, restricts the laser pulse rates that can be used. Rarely does the application favor the digitizing approach if the number of pulses must be limited to 20 or 30 % of a system that records multiple events and has a laser pulse rate 4 or 5 times as great. The one possible exception may be in mapping brush in the 1 to 2 meter height range, and only then because the

typical laser pulse length causes a dead time between successive events that can be recorded by the multi-event timer. It should be noted that in experiments conducted by NCALM in dense floodplain forests with mixed hardwood and pines and significant understory vegetation, high pulse rates and narrow beam divergence enabled accurate and robust penetration to the ground.

III. Calibration, Calibration, Calibration

Even the best ALSM instruments require careful and frequent calibration. It simply is not technologically possible to build a compact sensor head and electronics that are immune to the high vibration, variable pressure and temperature, impacts of rough landings, varying orientation, and varying electrical supply typically encountered in a light aircraft operating at low altitudes. And there are natural aging and wearing processes of components, such as the laser pump diodes and optical scanner that would cause variations over time even if the system were mounted on an optical bench in a clean stable environment. The only way to know the performance of a system during any given data collect is to design the data collection to reveal calibration errors or changes in performance. As a result, the importance of diligent and evolving calibration procedures cannot be overemphasized. NCALM employs "best practice" procedures that yield the highest data accuracy possible balanced against the need to maintain deployment flexibility. Depending on the particular science goals and area to be imaged, procedures in the field are adapted to achieve the required accuracy in the most cost efficient manner.

Manufacturers provide calibration parameters for the units they build, including values for the offsets among such components as the inertial measurement (IMU), the scanner, and an exterior point to which the GPS antenna is to be referenced. These mechanical dimensions typically are stable to the millimeter level or less, and there is no need for operators to open the sensor to measure these parameters between regularly scheduled factory cleaning and servicing. However, the manufacturers also typically provide "estimates" of such parameters as the zero point and scale of the scanner and biases (alignment offsets) in the roll, pitch, and yaw gyroscopes that can and do change significantly with time. Accurately knowing these parameters on a flight-by-flight basis is important because erroneous values can result in artifacts in the

delivered observations and derived products that users may interpret as "signal" in their applications.

Research quality data must be collected with an ALSM system that is calibrated regularly, preferably on a flight by flight basis. The details of how the calibration is performed may vary from project to project, and as environmental conditions vary. For example, the greater the flying height the more critical calibration parameters such as the scanner zero point and scale, and the gyroscope roll, pitch, and yaw biases become. If other constraints, such as rough terrain, require operating at a higher altitude, greater care in determining the calibration parameters must be exercised.

Prior to deploying on extended campaigns, NCALM flies lines orthogonal to the airport runway in Gainesville, which has been surveyed with tens of thousands of kinematic GPS points. Using an exhaustive nearest-neighbor point-by-point comparison procedure between the GPS and the lidar returns (not merely the lidar DEM), the zero point and scale of the scanner are accurately estimated to eliminate the well known "smile/frown" artifact to the few centimeter level. In fact, upon initial characterization of the new Gemini unit, NCALM observed and characterized a laser-pulse rate dependency in the scanner scale that several Optech personnel were not even aware of. NCALM also flew extensive test flights with the Gemini over areas of the UF campus and nearby forests that were well characterized with ground truth. The hard surfaces of parking lots and roofs on campus allowed us to determine the rms errors in the Gemini elevations as a function of laser pulse rate and scan angle. Over the forest test site, foliage penetration was characterized as a function of return number $(1 - 4)$, laser pulse rate, and beam divergence. Through these early tests, NCALM developed strategies for acquiring data that trade off requirements for rms error, spatial sample density, and foliage penetration, and which have already proved invaluable for acquisitions over forest-covered tectonic faults. NCALM will continue to run similar and additional tests in the future so that the system is always well characterized and data acquisition strategies can be tailored to the particular terrain and science goals of each project.

When on deployment, additional calibration should be done in the field before the scientific data collection begins. NCALM field crews use kinematic GPS to survey ground lines on hard surfaces, such as roads and runways, together with orthogonal ALSM swaths to check calibration parameters on a flight-by-flight basis. An example of the NCALM approach to calibration in the field is shown in Figure 2.
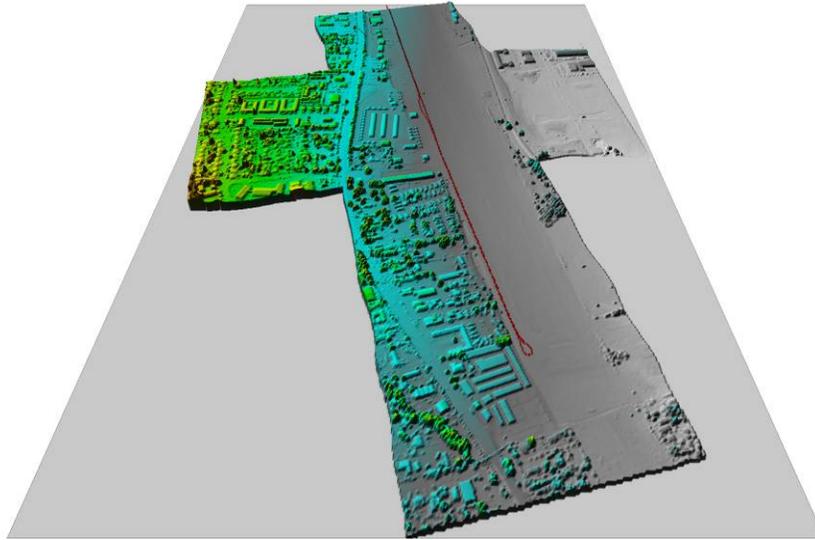
Figure 2: Orthogonal ALSM calibration swaths taken over an airport used during a deployment. Kinematic GPS ground points (shown in red) are used to calibrate the system in the field.

3.1 Planning and Executing ALSM Data Collections

Developing the best possible flight plan to obtain the highest quality ALSM data for a specific application requires extensive communication between the eventual user of the data and the ALSM data providers. Once in the field, collecting research quality ALSM observations requires the collaboration of an experienced ALSM operator and pilot. The aircraft must be equipped with a real-time navigation display to enable the pilot and operator to follow the flight plan, (i.e. to stay on line and at the planned altitude) very accurately. In areas with large changes in the terrain surface height, the flight plan must include preplanned climbs and descents of the aircraft to maintain uniformity in the ground point spacing. In particular, rapid climbs and descents must be avoided to maintain minimal pitch angles, and minimal roll turns employed to help maintain matching altitudes on overlapping flight lines. Figure 3 shows an example of a flight line pre-plan from an NCALM project that required changes in the heading and altitude of the aircraft during the laser on time. The NCALM ALSM operator uses this information to alert the pilot to upcoming maneuvers.
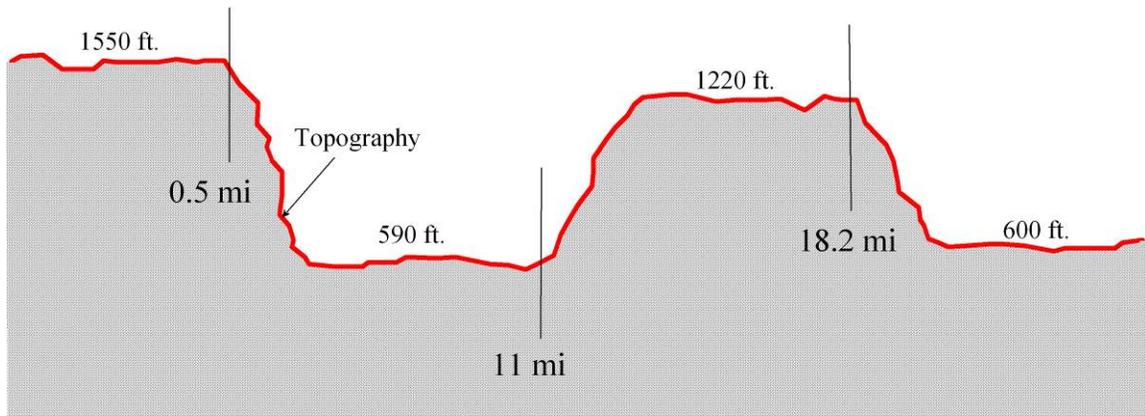
Figure 3: An example of NCALM flight planning. Topographic profiles of the site (along planned flight lines) are used to schedule maneuvers, such as climbs, descents, changes in heading, to ensure maximum data uniformity.

In addition to collecting data at much lower altitudes than do commercial providers (typically 600 meters AGL), NCALM overlaps parallel swaths by 50% or more. This provides points for correcting trajectory biases between swaths, yields higher point density on the ground, and provides added redundancy. NCALM also flies special "crossing" lines perpendicular to the primary mapping swaths to check for offsets between swaths and any residual scanner scale biases that might occur if the site is at a significantly different elevation (hence different temperature) than the airport from which the aircraft deployed. Climate control inside the NCALM aircraft also helps to reduce temperature effects.

3.2 Using Kinematic GPS to Determine the Aircraft Trajectory

Even when using a well calibrated state-of-the-art ALSM unit operated by a skilled operator/pilot team, the data collection will not yield research quality observations if the position of the aircraft at the epoch of each laser shot is not accurately known. Errors in the aircraft position map directly into errors in the final coordinates of the surface to be mapped. From the first ALSM flight made by UF researchers, Dr. Gerald Mader of the National Geodetic Survey (NGS) has been retained as an expert advisor on deriving the most accurate kinematic aircraft trajectories. Dr. Mader developed and has refined the Kinematic And Rapid Static (KARS) GPS program over more than two decades, and for many projects he has personally reduced and analyzed the aircraft trajectories for UF and NCALM ALSM data collections. NCALM staff at UF are very experienced with developing trajectory solutions with both KARS and other GPS

programs. If disagreements are found in the resulting trajectories, the issue is followed up and resolved. No facet of ALSM has received more attention than developing methods to obtain the highest possible accuracy aircraft trajectories.

Errors associated with the ionosphere are virtually eliminated by using geodetic quality LI and L2 receivers, and using only integer fixed solutions. Multi-path errors are minimized by using choke ring antennas at ground stations and a phase center calibrated antenna on the aircraft. The largest remaining errors are generally those associated with the changes in the path length as the signals propagate through the troposphere. There are two common approaches to minimizing errors in GPS observations at ground stations caused by the troposphere: (1) restricting the zenith distance of the observations collected (the cut off is typically set at 15 degrees altitude), and (2) correcting the observations for atmospheric effects using meteorological observations to better estimate the atmospheric delays. However, another approach, which has been used effectively for both GPS and very long baseline interferometry, is to collect observations over as large a range of zenith distance as is practical, and then use the observations themselves to estimate parameters in an atmospheric model.

All of these approaches become more difficult in kinematic positioning, particularly when the moving vehicle is a light aircraft flying in the often turbulent lower atmosphere. UF researchers and graduate students have tested the use of barometers and thermometers at the ground stations and on the aircraft, which were reduced using a modified version of KARS, but the results were mixed. As a result, NCALM has taken a conservative approach to determining the aircraft trajectory. The typical flying height is 600 meters, and adjacent swaths are overlapped by 50% or more. At least two ground stations are always used and more are used as needed to always have the aircraft within 20 to 25 kilometers from a ground station. Existing survey markers installed by NGS, USGS, or other agencies are not sufficiently stable in general to assume that the published coordinates are accurate enough to use as the locations of the ground stations. Rather, the current coordinates of all ground stations must be determined with respect to Continuously Operating Reference Stations (CORS) in the region. An example of the differences in orthometric heights along coastal Florida is shown in Figure 4.
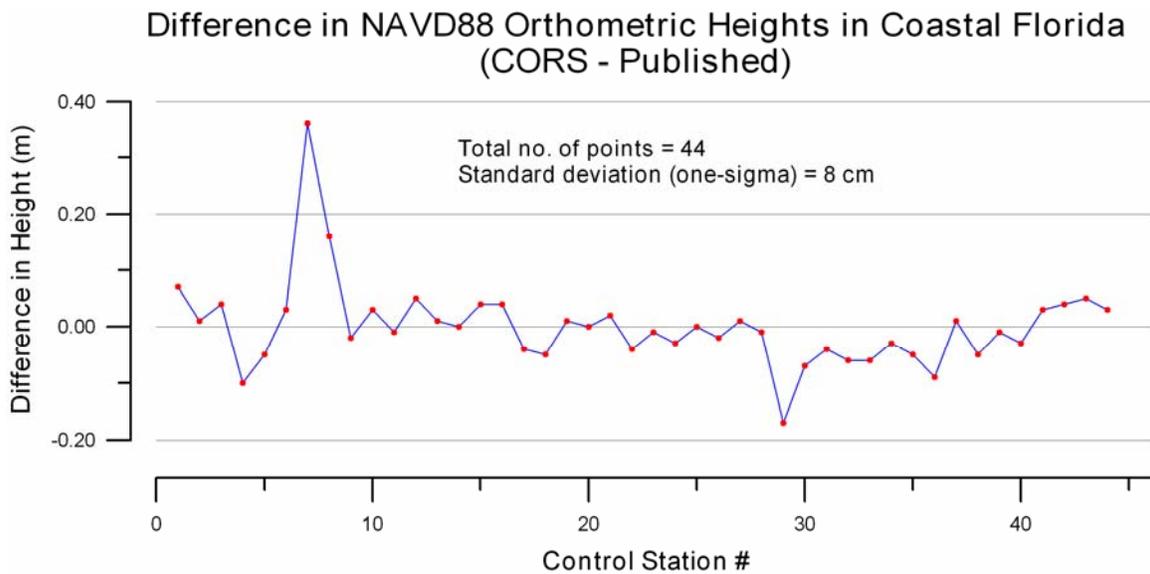
Figure 4: Discrepancy in published orthometric height along coastal Florida

Even following these guidelines there is usually a vertical bias in the ALSM observations that must be removed by comparing the heights to surface "calibration lines" determined by ground based kinematic GPS methods. Experience based on many hundreds of swaths show that this approach reliably yields final heights accurate to 4 to 8 cm. [Shrestha, *et al*., 1999]. Recent work by Ohio State University (OSU) researchers for the B4 Project, for which NCALM acquired and processed the ALSM data, suggests that it may well be possible to "calibrate" the atmospheric effects on the GPS observations using data from many ground stations with the aircraft flying at a range of altitudes [Shan, *et. al*., 2007]. This remains an open area of research in which NCALM stays abreast of the state of the art and updates its "best practice" procedures as warranted by the new knowledge. The academic orientation of NCALM ensures that procedures do not become "frozen in time", which can occur with some ALSM providers that have a "that is the way we have always done it" philosophy.

To conclude this discussion of accurately determining the aircraft trajectory, which is absolutely essential to obtaining research quality ALSM observations, it is important to point out that this is the single most common cause of excessive errors in ALSM observations collected by commercial companies. Most companies process the GPS observations with standard software provided by the manufacturers and assume that the resulting trajectories are accurate, even when artifacts revealing sizable errors are clearly evident in the data.

IV. Data Reduction and Processing

After the ALSM system has been properly calibrated and the data acquired using sound field practices, it is necessary to reduce, edit, filter and analyze the data in order to deliver the best possible product to the PIs.

4.1 Initial ALSM Data Processing and Reduction

The initial reduction of ALSM observations is performed using proprietary software developed by the manufacturer, and can be done by nearly anyone with reasonable computer skills. The technician must be able to recognize any abnormalities that may be caused by software malfunctions or data problems. Most common problems are rather easily spotted, but occasionally there are glitches that require consultations with the manufacturer. However, the initial reduction of the ALSM observations is usually done with a *preliminary* aircraft trajectory. When Optech first developed their system they assumed that the aircraft trajectory would be computed by the "built-in" program. Nearly immediately, UF researchers requested that they be able to replace the standard trajectory with one computed by other software, of the user's choice. Comparing the surface coordinates produced with the "standard" trajectory and trajectories computed externally by other programs, quickly proved that the KARS program developed by Dr. Gerald Mader, produced far superior results, virtually eliminating swath-to-swath vertical biases and tilts found in data sets processed with trajectories from other programs. This point is important. When using sub-optimal GPS processing, which often occurs in the ALSM industry, the resulting errors in the trajectories require much more extensive post-processing to "merge" the data from multiple flight lines. When the proper care is taken to produce highly accurate trajectories, the need for much of the post-processing "fixes" described in some papers is greatly reduced.

4.2 Filtering of ALSM Data

After reducing and editing the observations, the next major step is to filter the data set. There is not space here to discuss the many types of filters developed by many different researchers and companies during the past decade. Most filters are used to "remove" vegetation

and buildings, to yield "bare earth" points (see [Sithole and Vosselman, 2004] and [Zhang, *et al*., 2006] for a review). There are other filters with different goals, such as extracting three dimensional point clouds that represent returns from trees that contain information such as the biomass of stands of trees (see for example [Cho and Slatton, 2007; Lee, *et al*., 2005; Starek, *et al*., 2007]).

Because of the huge numbers of points in modern ALSM data sets (e.g. 10^{10} shots × 4 returns per shot for a recent NCALM project), filtering must be computer automated. But, selecting the filtering algorithms and parameters for the particular terrain and science objectives of each project, remains an art, and requires a significant amount of interactive processing. Ultimately, the filtered output must be reviewed by a person with knowledge of the terrain and the scientific application intended for the data, to determine if the filtering has been optimized. This point cannot be overemphasized. While NCALM strives to find and develop optimal and robust landcover filters, no single filter (even adaptive ones) will be optimal over all terrain features. To achieve optimal results for the particular science goals of each PI, the type of filters used, their inputs, and their parameter settings are functions of what surficial features are most critical to preserve. NCALM personnel at UF and UC Berkeley have years of experience in carefully checking filter outputs and determining how best to filter the data.

The most common problem with filtering of ALSM observations is retaining sufficient detail of the bare earth surface, while removing vegetation and buildings. All too often, particularly in steep terrain, nominal filtering may round off ridge lines or stream banks, or even clip the peaks off of steep hills. Figures 5 and 6 shows examples of two different areas initially processed with nominal filter parameters, the resultant artifacts in the DEMs, and the revised DEMs after the filtering inputs and parameters were tailored for the known geomorphology of the areas. This value-added processing is made possible by the significant time spent at each field site by the NCALM crew to learn the terrain, consultation with the science PIs for each site, and attention to detail. The diligent quality checking by trained and experienced NCALM personnel makes a dramatic difference in the final delivered data products.

Figure 5a: Marshall Block 1 detail view: unfiltered shaded relief map of the area. Note heavy forest cover and lack of surface detail.
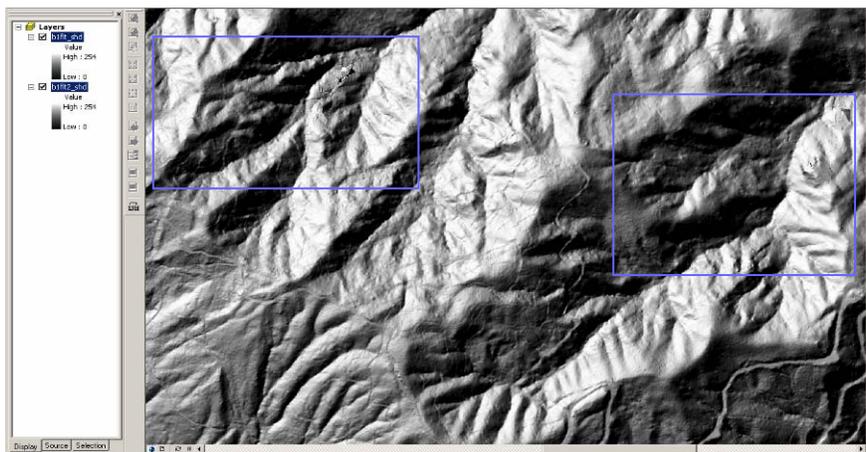
Figure 5b: Marshall Block 1 detail view after initial filtering. Note loss of detail caused by low density of ground points and the subsequent interpolation (krigging) artifacts.
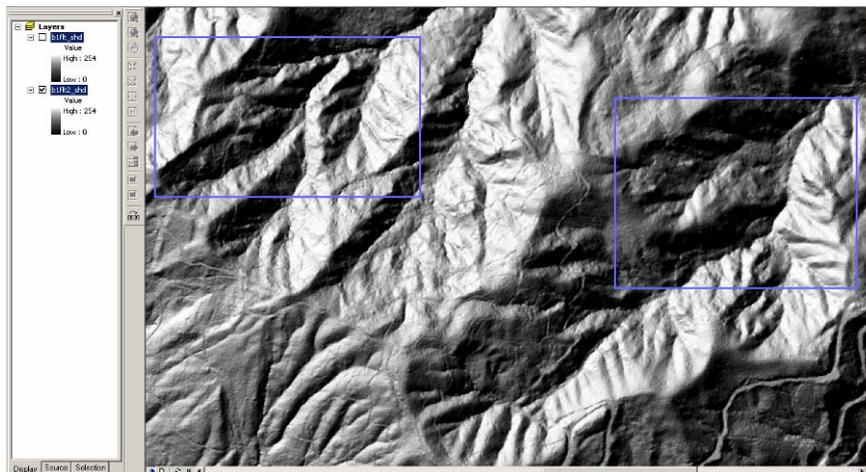
Figure 5c: Marshall Block 1 detail view after filter tuning. Slopes and ridges are better preserved.
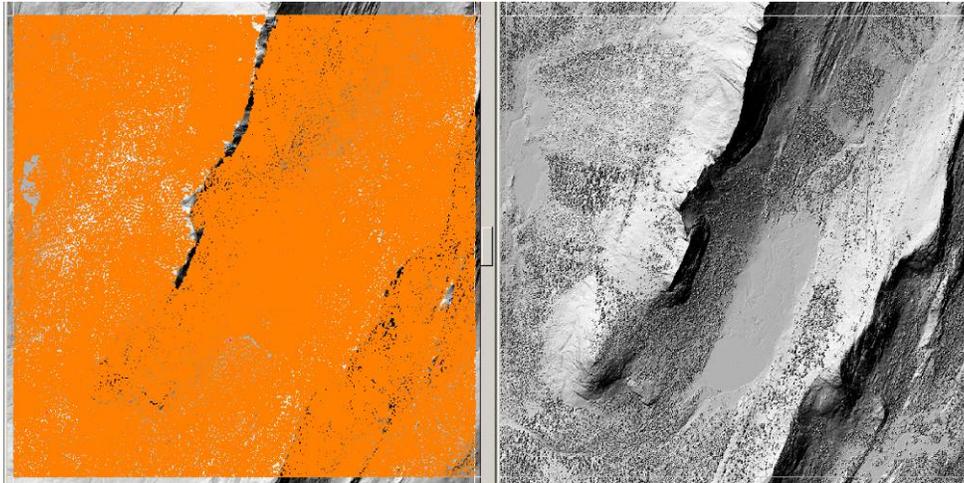
Figure 6a: Yosemite Block 25 detail view. Initial filtering omitted points on the tops of very sharp ridges (orange = points classified as ground)
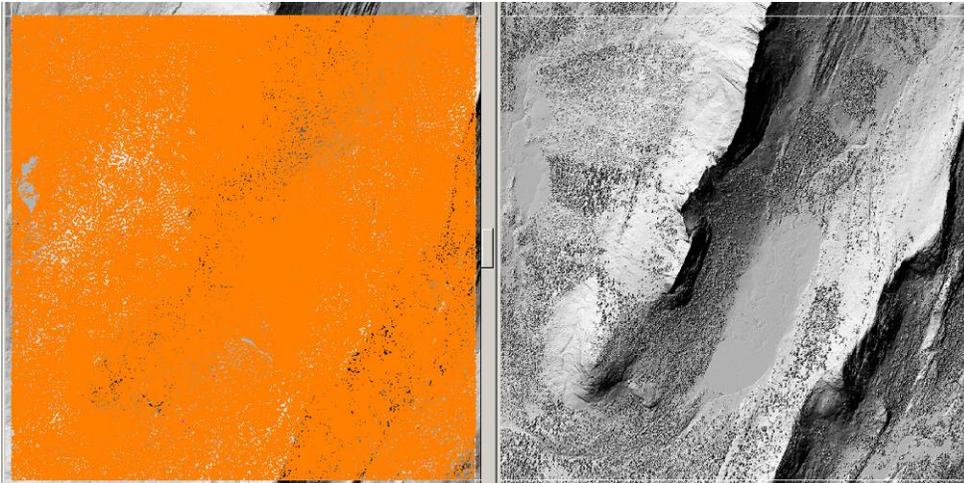
Figure 6b: Yosemite Block 25 detail view. The main ridge is far better preserved after semi-manual classification and filter tuning.

4.3 Intensity Normalization

As mentioned above, the intensity data collected by current commercial ALSM systems is a relative measure of the strength of each return pulse. The data capture circuitry generally allows for recording intensity values with 8 to 12 bit precision within an allowable minimum and maximum range that are determined by the particular aperture used and detector design. The intensities of reflected laser returns detected by an ALSM system are affected by the following factors: variations in path length, surface roughness and orientation, beam divergence, object

spectral properties (directional reflectance), object optical density, attenuation of the signal through the atmosphere, and ALSM system characteristics. While intensity calibration that accounts for the terrain's directional spectral properties remains an open area of lidar research, normalization of intensities based on path length is fairly straightforward to implement. NCALM normalizes intensities for path length variations as part of its standard processing. Before this normalization became standard procedure, NCALM performed it on request, and we issued an online report that described the procedure and provided three separate versions of the source code for the three most widely used C compilers so that users of older NCALM data could easily apply the normalization. When necessary, NCALM also updates the intensity normalization due to changes in system behavior over time.

V. Education and Knowledge Transfer

5.1 Graduate Student Hands-on Involvement

An important distinction that sets NCALM apart from all commercial providers is that rather than protecting "proprietary" processing techniques and software, we actively encourage direct participation in the processing of ALSM data by graduate students whose research involves using NCALM ALSM derived products and leads to publications available to the public. To date, many students at Universities across the country have taken advantage of this unique opportunity to come to the UF Campus in Gainesville or the UC Campus in Berkeley to sit at the elbow of experienced ALSM processors and be directly involved in the processing of their data. A short list of the students who have participated includes Ali Farid (University of Arizona); Kristin Gardener (Montana State University); Kurt Frankel (University of Southern California); Jill Marshall (San Francisco State University), and Quin Robertson (Florida International University). Through a Seed Grant program, NCALM also awards ALSM data collections on a competitive basis to graduate students from across the country needing ALSM data for their research.

In addition to students from outside institutions, many graduate students in various different areas of specialization at both UF and UC have also had direct interaction with ALSM processing in order to better understand the nature of their data. These students form a truly

interdisciplinary user group coming from earth science, forestry, civil engineering, and electrical engineering. The exposure of UF students to the ALSM data is further broadened by course work through the introduction of a graduate engineering class dedicated to lidar system understanding and data processing. It is the second class in a two-course remote sensing sequence that was developed in the UF Civil Engineering Department to ensure a pool of graduate students able to conduct research on a variety of lidar-related topics.

5.2 New Algorithm Development and Knowledge Transfer

Extensive algorithm development for improved ALSM processing and for extracting information from ALSM data is ongoing at UF and UC Berkeley. The projects and papers are too numerous to cite exhaustively here, but examples include adaptive vegetation filtering, estimation of sunlight penetration into forest canopy, segmentation of individual tree canopies for estimating crown volume, detection of small streams in forested watersheds, identifying morphological predictors of shoreline change, robust segmentation of buildings from vegetation in suburban areas, and extended baseline GPS ambiguity resolution. Some of these algorithms may eventually be implemented in an operational form for NCALM processing. But even those that remain as specialized tools, become available to NCALM PIs by virtue of their publication and through collaborations with NCALM staff.

In addition to research and development of new algorithms, various issues not suited to scholarly publication, but useful nonetheless, are made available on the Web as Geosensing Engineering and Mapping (GEM) Center Reports [LEN, 2007]. Examples include, basic point gridding to form DEMs, non-adaptive but multi-scale vegetation point filtering, and intensity normalization. Source code is provided in most of the reports. In particular, the intensity normalization report provides a basic description of why intensities must be normalized and gives the source code for three separate versions of the algorithm for the three most widely used C language compilers [Starek, *et al*., 2006]. NCALM PIs have expressed their appreciation for making this available and it has been cited in at least one ISPRS journal publication [Höfle and Pfeifer, 2007]. These reports will soon be augmented by the addition of more filtering algorithms packaged into a user-friendly graphical user interface by Dr. Keqi Zhang of FIU (NCALM member).

VI. Concluding Remarks

6.1 Warning Flags

      As we mentioned in the introduction, anyone with enough money can purchase a state-of-the-art ALSM system, hire a pilot, operator, and data processors, and bid on advertised projects, claiming that they will deliver research quality data. However, if they do not have the requisite knowledge and experience, they often will make statements or claims in their proposals or negotiations that reveal their lack of qualifications. Some of the most common statements that should serve as warning flags are listed in Table 2.

Table 2: Examples of common "warning flag" statements made by ALSM data providers that reveal a lack of qualifications.

"*Our system does not record intensity data, but you don't need it because we have automatic gain control.*" The final data will often have artifacts caused by range walk.
"*We use nothing but NGS marks for our ground stations and get the coordinates from the NGS data base, so there is no need to tie to CORS stations.*" Data collected using different base stations will often have offsets of decimeters.
"*We have registered professional land surveyors on our staff, so you can be assured that the final coordinates meet national mapping standards.*" Most registered land surveyors have no training or experience in mapping with ALSM. They will often check a few ground points and "certify" that the data meets national mapping standards.
"*Our system is calibrated twice each year and is certified by the manufacturer to meet their performance specifications, as long as the environmental conditions are within the stated ranges.*" The observations delivered will often have a variety of artifacts caused by biases in the IMU and scanner.
"*We use a standard software package to reduce the GPS observations and obtain the aircraft trajectory, and as far as we can tell, it works very well.*" The final data will often display artifacts caused by vertical offsets and slopes between swaths, and less often will display horizontal offsets, particularly along the direction of flight of each swath.
"*We do not waste money on large overlaps of adjacent swaths because we cut the edges of the swaths and discard that data anyway before we deliver the final data set to the user.*" The data will often have vertical offsets along straight lines where the swaths have been trimmed and the overlapping data discarded.
"*No, we don't use choke ring antennas at the ground stations. They are too large and heavy for the field*

crew, and we find that our regular land survey antennas work just as well." The data will often display artifacts that can be traced to apparent periodic changes in the location (particularly heights) of the reference stations, caused by multi-pathing of the GPS signals.

NCALM has acted as an outside consultant in assessing problems in commercially provided ALSM several times in the past. An example of this occurred in Alachua County, Florida when the Alachua County Government funded NCALM for an independent assessment of poor-quality ALSM collected and processed by a commercial vendor.

6.2 In Conclusion

Producing *research quality* ALSM observational data and derived products begins with using a well calibrated state-of-the-art sensor, which is necessary but not sufficient to guarantee favorable results. Even more important factors are the knowledge, experience, and skills of the personnel who carry out each step of the process, which include calibrating the instrument, flight planning, flying the aircraft, operating the ALSM sensor and supporting instruments, reducing and editing the raw point clouds, examining the data for artifacts and reprocessing to remove or minimize artifacts, filtering the observations, and inspecting the filtered data to make sure that important information has been retained.

NCALM is uniquely qualified to collect and deliver research quality ALSM data. In fact, it may be the only organization in the United States that currently has all of the requisite instruments and skills to routinely provide research quality ALSM data. NCALM makes use of the state-of-the-art Optech Gemini system, which operates at pulse rates up to 167 kHz, records up to 4 stops (including the last stop) per shot, uses weak and strong signal channels with constant fraction discriminators and a signal strength versus range bias look-up table to remove range walk, and records 12-bit intensity values for each stop.

UF researchers were the first in the nation to focus on the application of ALSM to terrain mapping for scientific applications, beginning with a filed test in 1996. UF was the first academic institution in the nation to purchase an ALSM system, and it has continued to update the system as the technology has advanced. The UF team is composed of geodesists, a registered land surveyor, and electrical engineers with instrument and signal processing expertise.

The UCB team has extensive computer processing and data archiving expertise, data filtering experience, and internationally recognized scientific achievements in the research of

geosurficial processes. The UF and UCB teams, which together form the core NCALM team, have more than four years of working collaboratively, drawing on the individual and combined skills of the staffs and graduate students, to complete nearly 100 projects (includes non-NCALM projects) for academic and governmental researchers across the nation—delivering research quality data to meet a wide variety of applications.

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