INTEGRATION OF A PROFILING LIDAR WITH GEOSAR

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ABSTRACT

EarthData initiated a program for the development of a profiling lidar for use with its GeoSAR interferometric synthetic aperture radar. EarthData's specifications for this lidar were implemented and built by Leica GeoSystems. The profiler, based on the ALS-40 has been integrated with the GeoSAR radar system. The lidar provides high accuracy seed points used to assess and remove systematic errors, such as tilt, in the GeoSAR derived DEM and magnitude image mosaic. Additionally, lidar points provide quality control ground truth data points to assess the quality of the derived products. This adaptation is unique. Not only does the lidar operate at over 30,000 feet above ground level, but also provides the accuracy to assess and correct systematic errors in GeoSAR derived DEMs and magnitude images. Results and analysis of the bore sighting and accuracy tests of the lidar points compared to an existing high accuracy DEM will be presented.

BACKGROUND

GeoSAR (radar) is a state-of-the-art dual-frequency X- and P-band interferometric synthetic aperture radar mapping system flown on a Gulfstream-II aircraft. Unique to this system is a P-band interferometer designed specifically to penetrate vegetation canopies and obtain true ground surface digital elevation models (DEMs). Radar signal data is collected in either an 80 MHz or 160 MHz mode for both the X- and P-band radars. Left and right looking antennas provide the capability of simultaneously mapping on both sides of the aircraft in the X- and P-bands, yielding four looks at each point on the ground (Figure 1).

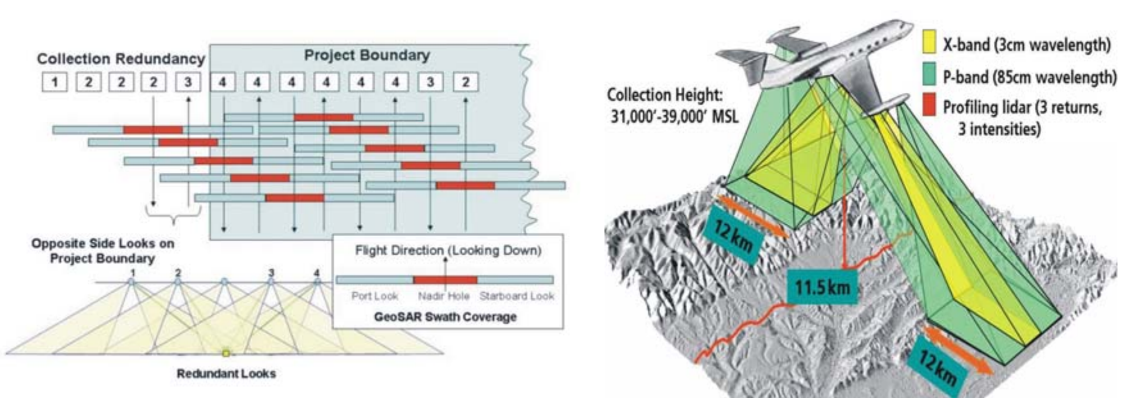

Figure 1. GeoSAR data acquisition

The X-band antennas are located under the wings of the aircraft while the P-band antennas are located in wingtip pods. GPS/IMU units and a measurement system are used in locating the wingtip antenna phase centers to determine the interferometric baseline. On-board high-speed data recorders are used to record both the IMU/GPS navigation data and the raw signal data from the X- and P-band radars. The data collection rate is over 100 square kilometers per minute, 5-meter post spacing, from an altitude of 10 kilometers. On-board disk capacity allows for up to 6 hours of signal data.

The GeoSAR system provides an end-to-end functionality resulting in the generation of a wide variety of mapping and remote sensing products. Core GeoSAR system functional components include:

a. Integrated management and production tracking
b. Mission and flight planning
c. Gulfstream-II-based dual-frequency airborne IFSAR data collection
d. Ground based IFSAR processor to create raw mosaicked GeoSAR products
e. DEM edit and product generation

The GeoSAR system was designed to acquire and process radar signal data in order to produce products compliant with map accuracy specifications for a wide variety of commercial and government users. The system's design specifications for mapping products are presented in Table 1.

Table 1. GeoSAR design specifications for mapping products

Description	X-Band	P-Band
DEM Height Accuracy	0.5 –1.2 m (Relative) 2.5 m (Absolute)	1–3 m (Relative) 2 – 5 m @ 5 km Altitude (Absolute)
Planimetric Accuracy	1 m (Relative) 2.5 m (Absolute)	2 m @ 5 km Altitude (Absolute) 4 m @ 10 km Altitude (Absolute)
DEM Resolution	2.5 – 5 m	2.5 – 5 m
Ground Swath Width	12 km on each side	12 km on each side
Polarization	V V	H & H V or V V and V H

While the IFSAR data is collected in strips, the raw products are output as a contiguous wide area mosaic (WAM). Ground processing transforms the raw strip data from SCH format to a WAM in a user selected coordinate system or projection. The mosaicked data are in a native 32-bit floating-point format that preserves the information content of the raw signal data. All raw GeoSAR WAM products are georeferenced, i.e., a pixel in the magnitude image corresponds to a post in the DEM. Also available are products such as 67-centimeter GSD orthorectified slant plane images that can be used as stand-alone products or as ancillary data.

PROFILING LIDAR

Lidar Installation

The lidar telescope is designed to be installed as a single unit within the pressurized compartment of the Gulfstream-II. The lidar unit is mounted on the aircraft centerline and under the floor. Installation on the Gulfstream-II required a 7" diameter window be cut in the fuselage for transmission and return receipt of the infrared laser beam. A pressurized glass window was installed in the opening. A fairing and protective door were installed on the outside to protect the glass from debris on take off and landing.

Lidar Specification

The lidar operational requirements are summarized as the system must:

- Be capable of consistently producing first, second and third returns from 30,000 feet of elevation above the terrain
- Be capable of being calibrated
- Produce a vertical accuracy better than 30 centimeters (1 sigma)
- Produce a representative percentage of vegetation penetration

The lidar profiler consists of (1) the sensor, equipped with the shutter/attenuator, laser transmitter, receiving telescope and electronics, and the IMU mounted on top, and (2) the computer rack, equipped with the system controller, GPS/IMU box, data logger, laser power supply, and a laptop control computer to operate the system in the aircraft. The complete system is shown in Figure 2.

The lidar profiler is equipped with a Novatel Millennium geodetic L1/L2 GPS receiver for accurate positioning and an Applanix POS/DG 510 IMU for accurate orientation parameters. The laptop control computer is a Panasonic

Toughbook CF-28 with a Pentium III processor and Windows XP Professional. The basic system characteristics are listed below:

- Variable pulse rate, 0 to 45 kilohertz (10,000 hertz at 30,000 feet above ground level)
- 1064 nanometer wavelength
- 4-Watt laser transmitter
- 0.15 millijoule peak power per pulse
- 8.5 nanosecond pulse width
- 3 ranges (first, second, true last) with 3 intensities (first, second, third)
- GPS/IMU data written to 512 megabyte or larger PCMCIA cards at < 0.025 megabyte per second
- Laser range data written to 36 gigabyte removable hard drives at < 0.4 megabytes per second
- 3 meter spot size at 30,000 feet above ground level
- 2 centimeter post spacing at 180 meters per second velocity

Differential GPS and IMU processing is done with POSPac Version 4.1.

Figure 2. Complete lidar profiler system with sensor (left) and rack (right).

Lidar Boresighting

The lidar boresight is a calibration procedure used to align the IMU and lidar roll and pitch reference frames. The driving factor in boresighting the profiling lidar is the requirement to acquire a target return with the 3-meter-laser beam from an altitude in excess of 30,000 feet above ground level. It was determined that a smooth gently sloping feature with a sharp edge was required. A high resolution and high accuracy digital elevation mode of the target area is also required. A calibration procedure was developed and verified for the profiling lidar boresighting during proof of concept phase. This process was integrated with flight operations aboard the Gulfstream-II and ground processing system.

Pitch may be measured by flying the same flight line in opposing directions. These flight lines should be flown in opposing directions perpendicular to a feature such as the peak of a uniform pitched surface. Although it may be impossible to have the two lidar scan lines fall directly on top of each other, if the lines are nearly perpendicular to the ridge peak they should provide a good measurement for determining pitch. Roll data are collected in flight lines perpendicular to each other. These data are collected along the large smooth sloped surface. Roll errors of the profiling lidar are typically small compared to pitch. The data of a profiler is minimally affected by heading because it is looking at nadir.

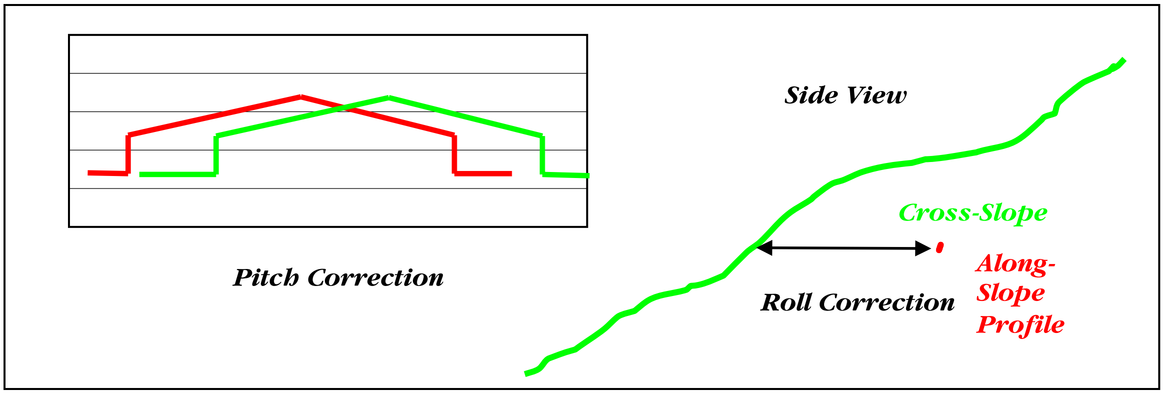

Figure 3. Boresite principle of a lidar profiler.

Boresight location for the initial lidar test flights on the Gulfstream-II was the Hansen Dam located in Los Angeles County, California. Hanson Dam was selected because of its proximity to the aircraft's base of operations, availability of an EarthData-generated DEM and the dam and its face meet the requirements of providing a smooth sloping surface that is ideal for boresighting the lidar.

Lidar profiler data was collected over the Hansen Dam at an altitude of 31,000 feet above mean terrain at a speed of 400 knots with a lidar pulse rate of 10 kilohertz, which translates to a 3-meter beam spot on the ground with a post spacing of approximately 2 centimeters. The boresight flight plan for the lidar profiler system consists of three perpendicular sets of bi-directional flight lines (Figure 4), across the face of the dam.

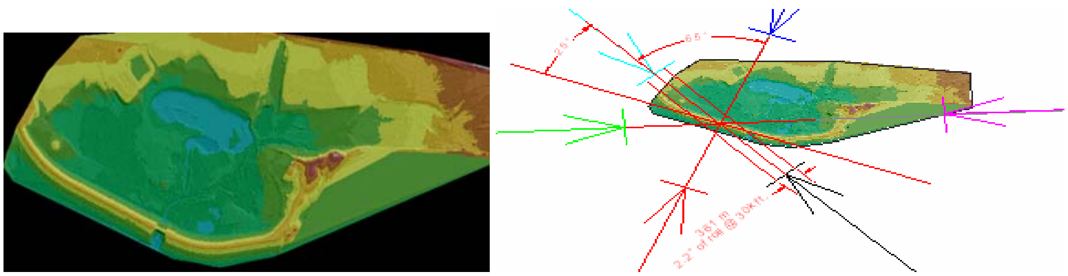

Figure 4. Hansen Dam elevation model and flight plan.

Data Processing

The data collection resulted in raw lidar return data; GPS base station data, and aircraft position and orientation data. The data were processed using standard EarthData procedures. These included:

- Generating the dGPS solution and creating the best estimate of trajectory using Applanix POSPac and Applanix POSProc, respectively
- Processing raw lidar shot data using Leica's ALS Post and the SBET to provide each return with a geographic/orientation reference, with output data in industry standard .LAS format
- Analyzing and visually inspecting LAS files for calibration and data quality assurance

Boresight Roll and Pitch Determination

The LAS lidar profiles were processed using an EarthData developed proprietary iterative measurement technique. The final roll and pitch corrections were -0.007788900 and 0.00653900 radians or -0.446° and 0.375°, respectively.

The angular corrections for the lidar profiler were entered into the ALS Post Processor, and the raw lidar data were reprocessed to produce the final profile .LAS files.

Accuracy Assessment of Boresight

The profiler lidar boresight accuracy was compared against the Hansen Dam digital elevation model. The DEM has a post spacing of 5 meters and a vertical accuracy of 15.1 centimeters.

Two data sets were averaged to generate a common set of average boresight angles and DEM z-bump. From these statistics estimates of the consistency between two boresights was confirmed.

$$\Pr\left[\left|\frac{S_n}{n} - \mu\right| \ge c\right] \approx 2\left(1 - \Phi\left(\delta\right)\right), \quad \delta = \frac{c\sqrt{n}}{\sigma}$$

$\Phi\left(\delta\right) =$ cumulative Normal Distribution

$\bar{X} = S_n / n = \text{SampleMean}$ $\mu =$ true mean of the distribution $c =$ threshold value

Equation 1. Consistency Metric

Table 2. Accuracy

Average Z-Error DEM Confusion Matrix Average Angles, <z-bump> = -0.653m					
Performance Results	w.r.t. Average Reference Angles				$\Pr\left[\left\|\frac{S_n}{n} - \mu\right\| \ge c\right]$
	RMS (cm)	Average (cm)	Threshold	δ	
31-Mar-05	17.4	-7.7	30.0 cm	3.845	1.20%
18-Jun-05	22.2	7.7	30.0 cm	3.528	4.18%

The average boresight and z-bump parameters (when applied to both data sets) yield an RMSE of about 20 centimeters, which is well below the 50 centimeters specification.

Figure 5 shows the correlation between the lidar profile and the Hansen Dam DEM (yellow points)

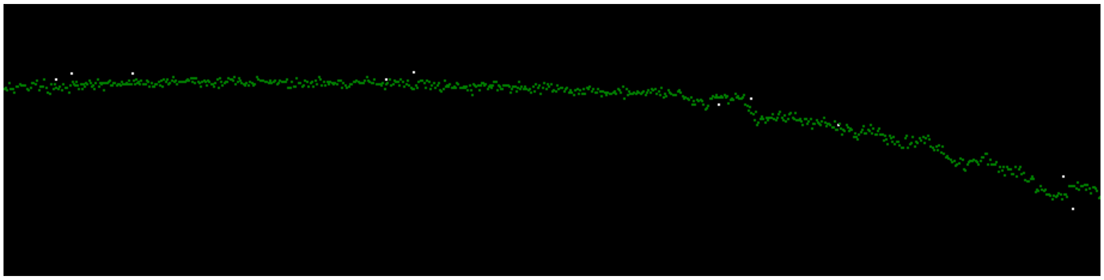

Figure 5. Correlation between profile and DEM

Lidar with GeoSAR Data Preliminary Results

On May 26, 2005, lidar profiler data were collected simultaneously with the signal data over a test site located in the vicinity of Los Angeles, California. The profiler data acquisition flight was designed to test the integration of lidar profiles into the GeoSAR mosaicking process. The collection was performed at an altitude of 31,000 feet above mean terrain at a speed of 400 knots (206meters per second) with a lidar pulse rate of 10 kilohertz, which translates to a 3-meter beam spot on the ground with a post spacing of approximately 2 centimeters. The flight plan consisted of one flight line centered along the track of the existing GeoSAR swath and two perpendicular crossing tracks located at the northern and southern extents of the GeoSAR swath. Figure 6 is a map of the collection area; the blue lines indicate the flight path for the lidar profiler data collection.

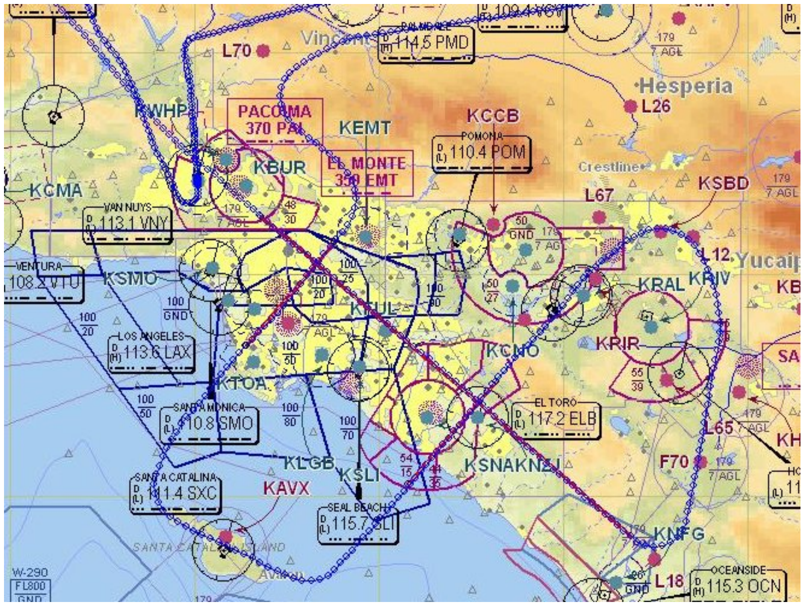

Figure 6. Lidar profiler flight plan.

Lidar-GeoSAR DEM Concept

The GeoSAR lidar profiler has a maximum three returns and an intensity associated with each return. The lidar data will overlap with GeoSAR X-band and P-band as multiple flights fill the geometric gap between the swath of a single datatake, as seen in Figure 7.

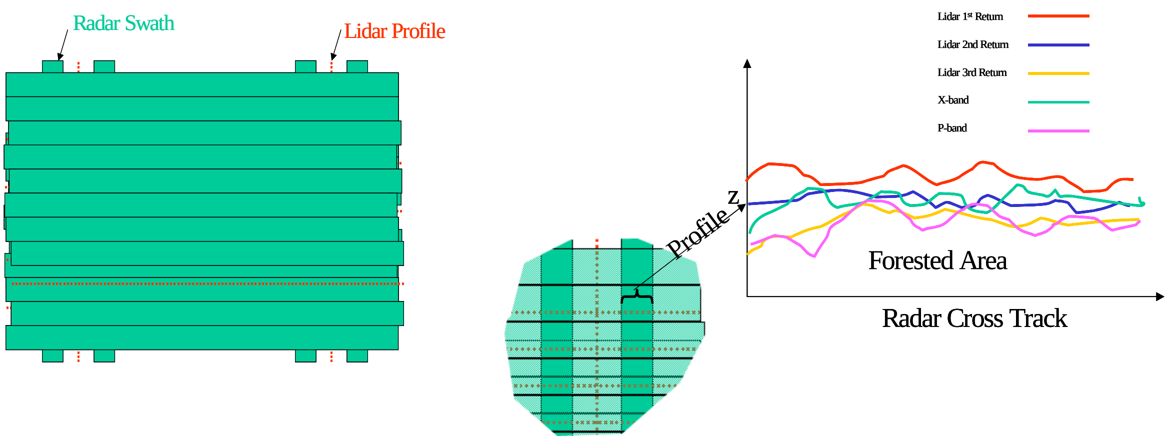

Figure 7. Lidar data overlap with GeoSAR X- and P-band data

The lidar data can be used to level the radar data for:

- Identifying the lidar return number with the radar data
- Using profile correlation algorithms to correlate the radar data with the lidar data along the radar cross track direction (the radar data has very little error along the flight direction)
- Analyzing the displacements of all intersections to adjust the radar data from tilt and datum shifts

PRELIMINARY RESULTS

At the preparation of this paper, the lidar-GeoSAR DEM algorithms are in initial testing and debugging.

SUMMARY

EarthData has successfully developed the profiling lidar concept. This lidar is the first of its kind implemented in conjunction with a dual-band interferometric radar system. A proof of concept performance test was carried out using an EarthData-owned Cessna 441 Conquest II and a Dynamic Aviation-owned Beechcraft King Air 200. Lessons learned from the prototyping were incorporated when transitioning the lidar to Gulfstream-II GeoSAR aircraft operations. A procedure was developed for boresighting the profiling lidar using a large naturally occurring or manmade feature with a smooth open face. Analysis of the lidar data with a high accuracy DEM verified the concept of a profiling lidar system and confirmed the ability to derive accuracies of 20-30centimeters from the resulting lidar data sets acquired at over 30,000 feet above the ground.

REFERENCES

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