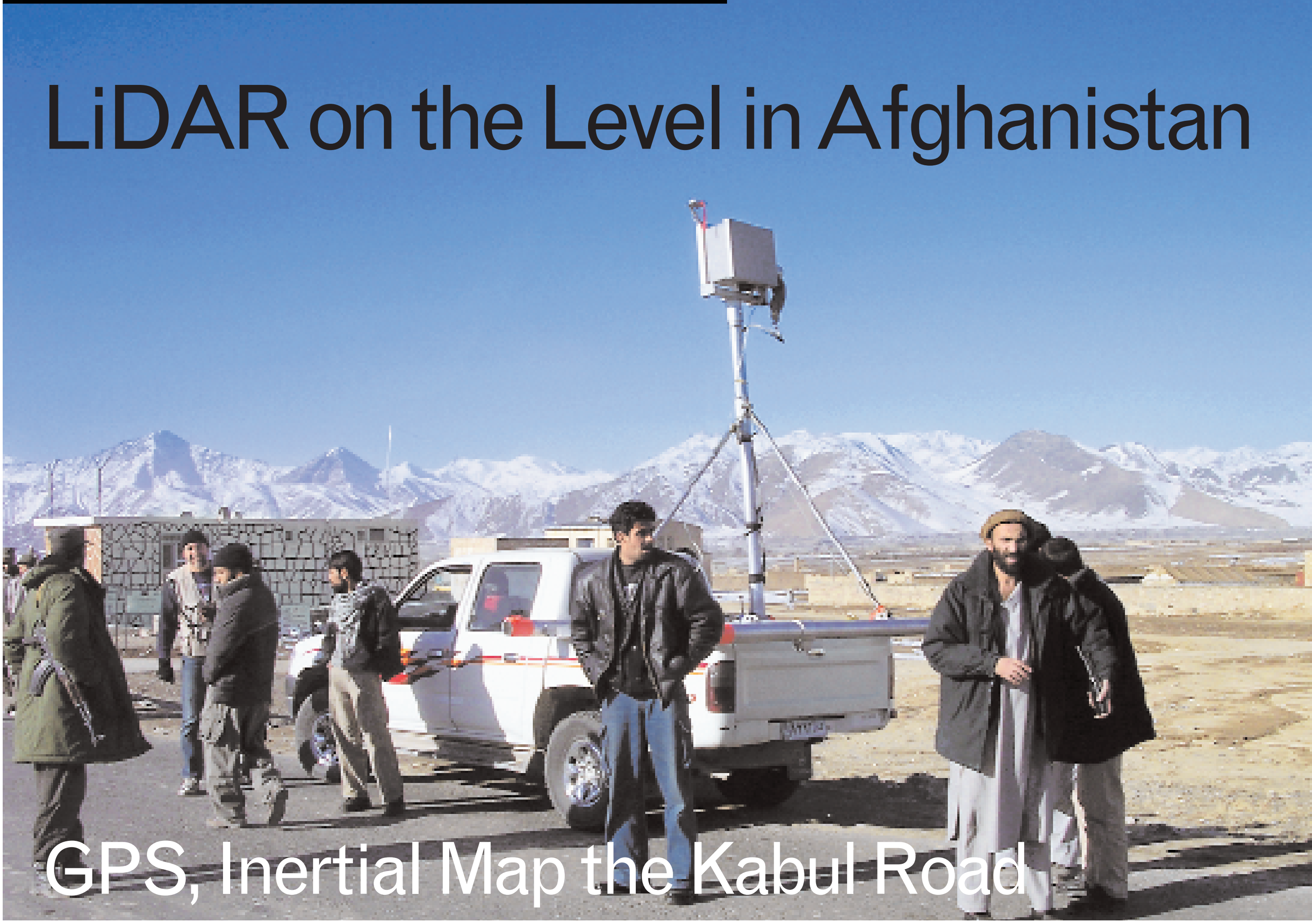
LiDAR on the Level in Afghanistan



GPS, Inertial Map the Kabul Road

Concerns about airspace security in Afghanistan literally brought a LiDAR-based survey operation down to the ground. Fashioning a truck-back system, Canadian engineers used GPS and inertial measurement to time and locate the laser-ranging "hits" that would construct a digital elevation model of the badly damaged highway. The return to an earlier prototype now affords a quick, cost-effective solution for other survey situations.

Simon Newby and Paul Mrstik, Terrapoint

Two years ago, traveling the 1,062 kilometers from Afghanistan's capital, Kabul, to the northwest city of Herat could take up to one week. The roadway, known as Highway 1, forms part of the country's ring road, connecting Afghanistan's major population centers. With more than 13 million Afghans living within 50 kilometers of the ring road, the corridor is a vital link for promoting economic activity and provides access to basics such as health care and education. Originally paved in the 1960s by U.S. foreign aid grants and the Soviets, its surface and several bridges had suffered severely from decades of neglect and lengthy wars. In the worst sections, speeds were limited to 10 kilometers per hour. Countless land mines hidden at the road edges made conditions even more hazardous and significantly prolonged travel times. As a result, reconstruction of this road became key to Afghanistan's economic renewal and to improvements in quality of life.

First Steps

With the Taliban removed from power and emergency aid programs in place, early in 2002 the U.S. Agency for International Development (USAID) established the Rehabilitation of Economic Facilities and Services (REFS) program. Designed to promote economic recovery and political stability in Afghanistan, the program includes repairs to water lines, sanitation services, electrical distribution infrastructure, and irrigation systems. Improvements in access to education, health, and government services are also priorities. The main focus of the REFS program, however, is the rebuilding of Highway 1 from Kabul to Herat.

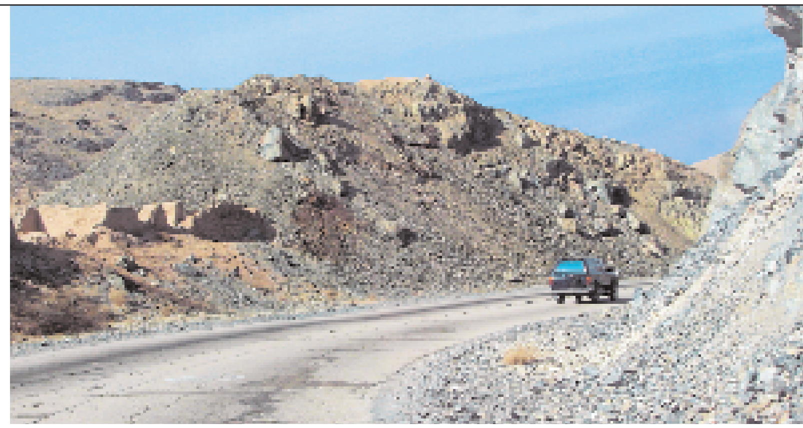
In September 2002, the Louis Berger Group, Inc. received the contract to carry out the REFS program. The $250-million highway reconstruction project was broken into two phases (see **Figure 1**) ; the first phase, covering the roadway from Kabul to Kandahar, began in November 2002, with several subcontractors secured to complete the work.

Before construction crews could move in to prepare for repaving, two major tasks had to be completed. Removal of land mines from the sides of the roadway, to make the area safe for workers and equipment, assumed first priority. As manual techniques moved too slowly to support the project schedule, the United Nations Mine Action Center Afghanistan (UNMACA) was brought in to assist. An armored vehicle drove along the highway shoulders, collecting frequent air samples. The samples, labeled with GPS coordinates, then went to Kabul, where mine dogs analyzed them in a controlled laboratory environment. This method greatly narrowed the contaminated area requiring clearing, and increased efficiency by 400 percent.

As the new road would cover the existing one, a survey of the existing surface came next in the sequence. Efficient material management and design planning require accurate survey data. During Phase I, crews used traditional ground-based techniques to survey the road surface. The survey between Kabul and Kandahar moved slowly, taking 200 days to complete. Upon completion of de-mining and surveying, Berger engineers began the process of grading and paving the highway in the presence of more than 1,000 security personnel.

New Survey Technology

Because of the laborious pace of the Phase I survey, project coordinators considered alternative survey methods when work began on the second phase: reconstruction of the section from Kandahar to Herat. In June 2003, Mosaic Mapping Systems (now Terrapoint), of Ottawa, Canada, learned of the requirements for an advanced survey and believed its airborne light detection and ranging (LiDAR)-based system would furnish an ideal solution. LiDAR measures the time-of-flight for a laser pulse to strike a point on the Earth's surface. A laser scanning system generates and receives the reflected pulse. The system integrates a GPS receiver to measure aircraft

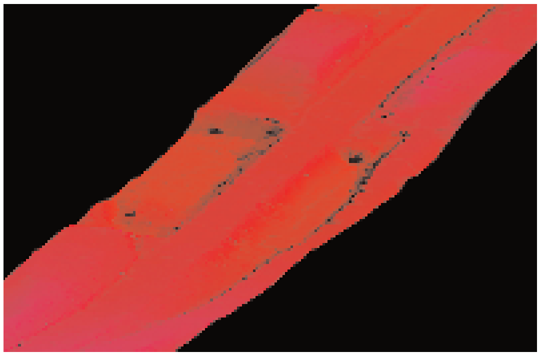


▲ **A SECTION** of the Kabul-to-Kandahar highway, found to be in better shape than most other segments prior to reconstruction. Travel on other stretches was often limited to 10 kilometers per hour due to poor road conditions.

◀ **FIGURE 1**
Afghanistan's ring road links the country's major cities. Reconstruction of the southern segment occurred in two phases.

position and the precise time of the pulse. An inertial navigation system monitors aircraft pitch, roll, and heading. Using the speed of light and pulse return time, the system determines the distance from the aircraft to the point on the surface that reflected the pulse. With known aircraft position and attitude, it then calculates the surface point's absolute position.

The laser pulses at constant intervals to create a grid of surface elevation measurements. The spacing between grid points, called point density or resolution, is a key parameter in the level of detail provided by the data. The combined accuracies of the laser scanner, the GPS receiver, and the inertial navigation system determine data accuracy. Data collected by the LiDAR system are assembled in a digital elevation model (DEM), a data file that contains the latitude, longitude, and elevation data for each of the points in the grid pattern. Three-dimensional graphics (see **Figure 2**) rendered from a DEM can depict the various features of the scanned surface. The data provide vital topographic information for applications such as road reconstruction, land development,



▶ **FIGURE 2** This computer-generated shaded relief representation of the highway was rendered from a digital elevation model.

flood risk mapping, power and pipeline corridor mapping, mining, and exploration work.

LiDAR System

Accurate and efficient data collection provided by LiDAR technology made Terrapoint's ALMIS-350 system a promising candidate for the Phase II survey. Typically installed on helicopters, the ALMIS-350 consists of a scanning laser, a tightly coupled GPS/inertial measurement unit (IMU) sub-system, and two computers — one for system control and logging, the other for flight navigation.

The system's laser scanner provides 10-kHz measurements, 20-millimeter measurement accuracy, 5-millimeter measurement resolution, and a 60-degree swath width. The GPS/IMU sub-system includes a GPS receiver capable of 2-centimeter real-time kinematic (RTK) positioning and a ring laser gyro (RLG)-based IMU with a 1-degree-per-hour drift rate. Combining GPS and inertial technologies makes positioning data available at increased rates (100 Hz) to meet the data capture capabilities of the laser scanner, while IMU-provided attitude data manage the high dynamics encountered in an airborne environment.

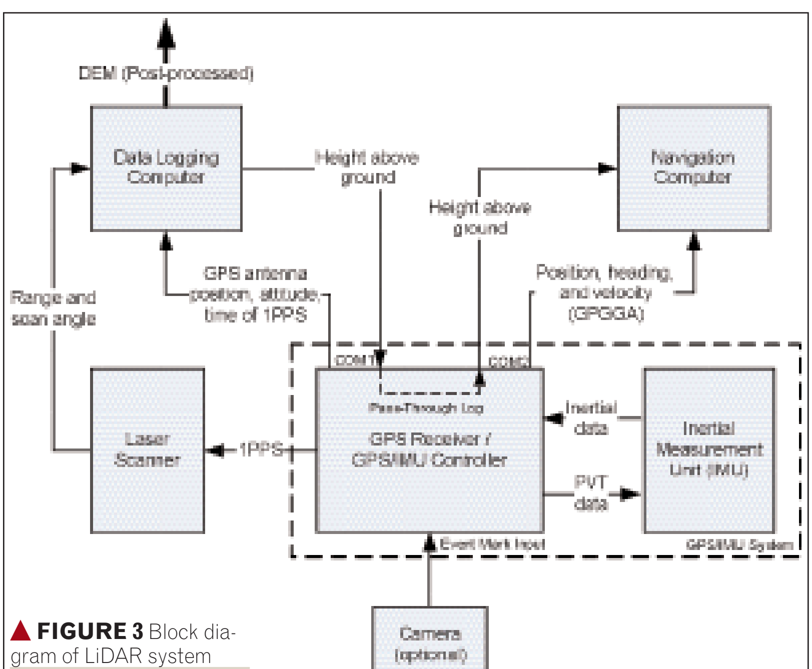
The IMU also enables continuous operation during short GPS outages by supplementing the GPS data with the inertial measurements, improving productivity.

Optionally, the system can carry a digital imagery system, in which case the GPS/IMU system's configurable event marker timetags the resultant imagery for correlation with the laser data.

The system (see **Figure 3**) synchronizes blocks of laser data to the 1 pulse-per-second (PPS) output from the GPS/IMU subsystem. The data logging computer records measurements from the scanner, consisting of the time-of-flight of the laser pulse and the scan angle at which the time-of-flight was measured, as well as data from the GPS/IMU, for subsequent input into Terrapoint's proprietary laser post-processor (LPP) software.

Proprietary software running on the data logging and navigation computers provides guidance to ensure parallel flight lines with sufficient overlap. Field crews establish a minimum of two dual-frequency GPS reference stations so that the baseline distance from reference station to helicopter does not exceed 15 kilometers. Double-differenced post-processing using Terrapoint's proprietary FlyKin Suite software package produces an aircraft trajectory typically accurate to within 2 centimeters.

Accuracy and point density of the resultant dataset are a function of the helicopter's velocity and flying height. For high-accuracy surveys, the system typically deploys at an altitude of 150 meters, flying at a velocity of 50 knots, producing a point density of the order of four points per square meter, with absolute vertical accuracy (95 percent confidence level) of ±0.05–0.10 meter on hard surfaces, ±0.10–0.25 meter on soft/vegetated surfaces (flat to rolling terrain), ±0.25–0.35 meter on soft/vegetated surfaces (hilly terrain), and absolute horizontal accuracy (95 percent) of 0.15–0.50 meter on all but extremely hilly terrain.



▲ **FIGURE 3** Block diagram of LiDAR system

Re-engineering for Ground

With these specifications, Terrapoint's LiDAR solution seemed ideal for the task. However, military experts suggested that an airborne approach might incur danger, given Afghanistan's state of unrest. In addition, finding an appropriate aircraft in the region proved next to impossible. These constraints created an opportunity for Terrapoint to revive work on an earlier prototype ground-based LiDAR system. Created only as a proof-of-concept, the prototype had not been further developed due to lack of demand for the device. Turning the proof-of-concept into a production data collection device brought about its own challenges.

System Conversion. Project engineers developed a basic design and data collection methodology after analyzing the specific project requirements, and determined that a frame-and-pole mount on the back of a pickup would offer the most effective yet simple approach. As they developed the mounting method before seeing the truck upon which the system would be installed, the mount had to be flexible and adaptable. Engineers did not know exactly what size of vehicle would be available, so they designed a frame to fit both large and small open-bed trucks.

They removed the laser scanner assembly from the helicopter pod and mounted it on the scanning pole without modification. The chosen mounting orientation meant designers had to devise a new method of aligning the IMU, and also incorporate the ability to align the system without leaving the road, for safety reasons. They replaced Terrapoint's proprietary digital camera solution with a commercial off-the-shelf high-resolution video camera data-collection system, and integrated it with the GPS/IMU system.

Pictures sent from the route to be surveyed in Afghanistan showed a variety of terrain and road conditions, so vibration and jarring of the scanner constituted key concerns, and indeed later proved to cause some problems on the roughest section of the road. In addition, the system, normally powered by a 28-volt supply for aircraft use, now had to draw from the truck's 12-volt supply.

Testing. Project crews conducted test drives of the system on a road running through Terrapoint's test course near Ottawa, normally used to verify airborne LiDAR data and image accuracy. Large amounts of existing helicopter LiDAR data in the same area, and the ground truth data derived from it, were used to check accuracy and repeatability. The system worked exceptionally well, although it later became clear that attempts at simulating the rough road conditions expected in Afghanistan were laughably inadequate.

The test course also helped verify that the chosen scan directions provided enough coverage while simultaneously keeping shadowing and reflections

▲ **DANGERS OF OVERFLIGHT** in Afghanistan forced adaptation of the LiDAR system originally designed for helicopter operation to a truck-back setup.

► **BACKSEAT** passengers comprised two computers, one for system control and logging, the other for route navigation

▼ **SHOTGUN SEAT** had responsibility for monitoring LiDAR operations en route.

to a minimum. High point density, at about 40 points per square meter, compared to four points per square meter for the helicopter-based system, required creative methods for coping with the large amounts of data being generated.

Phase II

With the conversion challenges addressed, Terrapoint introduced its new system as SideSwipe and, in October 2003, received the sub-contract to survey Phase II of the highway. The ground-based system was designed to use three passes to gain the necessary data. For each section surveyed, the crew first drove the road with the scanner pointing forward and tilted slightly down, executing a horizontal scan, sweeping a 60-degree swath. They then rotated the system to scan vertically from the side of the vehicle. In this configuration, the swath intersected the ground approximately 5 meters from the side of the vehicle and extended to nearly 100 meters. The same setup then scanned the surface to 100 meters out on the other side of the vehicle (see **Figure 4**).

A security contingent of 15 to 20 people accompanied the three-person Terrapoint team during the survey. Lead and tail vehicles ensured that the route remained free of potential harm. On occasions where it was thought to be unsafe to proceed, the convoy returned to a base location. With relatively few base locations providing adequate protection and facilities along the 566-kilometer route, the survey vehicle typically had to travel a long distance to and from the survey site on any given day, slowing progress.

Challenging Environment. Road conditions themselves also delayed completion. In ideal conditions, the SideSwipe system can acquire data at speeds of up to 100 kilometers per hour or faster. On Afghanistan's Highway 1, such speeds were not possible, with numerous occasions when the vehicle could only travel at one-tenth that pace.

Vibration was one unknown that could not be easily simulated. Road conditions in Afghanistan were described as very bad in places, with cracks across the road at regular intervals where the original slabs had deteriorated. Prototype testing at Terrapoint had gone smoothly, but the roads were smooth too, so testing was set up on a section of gravel road using pieces of lumber laid across the road at regular intervals. IMU noise or laser vibration problems were expected, but they didn't materialize at this stage.

The reality of road conditions in Afghanistan proved far worse. A long stretch of the road had deteriorated to the point where one could only drive at 10 kilometers per hour. Drivers try to cross those sections at the extreme edge of the road where it is in slightly better condition, and in fact the survey vehicle slipped off the road once while in transit, toppling the sensor package to the ground.

As the crew surveyed farther into the project, road conditions deteriorated further and the laser began to shut down when in the sidescan position, possibly because the encoder was slipping when subjected to excessive vibration. The team discussed and discarded various solutions. A partly effective solution involved changing the angle of the sensor package on the mounting pole to do the sidescan at a different angle. This significantly reduced the number of shutdowns, probably because the encoder belt ran at an angle less affected by vibration.

Terrapoint staff in Canada assembled and shipped a suspension system, affectionately known as the "bobblehead," that could slip onto the pole between the frame and the sensor package. This system actually eliminated the laser-head shutdowns, but it deteriorated after very few days of use and finally came apart, throwing the sensor package to the ground, an event the crew said was announced by the system reporting zero laser ranges.

Surprisingly, after all these adventures the system continued to work fairly reliably, albeit without the bobblehead and with occasional laser head shutdowns due to the road conditions.

GPS/IMU Performance. Although during prototype testing, the crew did test the GPS/IMU solution to traverse some obstructions such as going under a bridge, Afghanistan's barren terrain proved extremely GPS-friendly — wide-open skies with very few obstructions, so that operations seldom required this aspect of IMU supplementation. The IMU's main purpose in this application was to provide the orientation parameters needed to compute the coordinates on the ground of a laser "hit," as well as IMU coordinates at 100 Hz in conjunction with the GPS.

This produces a data log of time, position, orientation, laser time-of-flight, and laser mirror angle at 100 Hz. The laser data are very sensitive to small angular errors, and can behave like a 14- to 300-meter lever arm, magnifying IMU, timing, and positioning errors — so our goal became minimizing all positioning and orientation errors to achieve the required accuracy for a reconstruction survey.

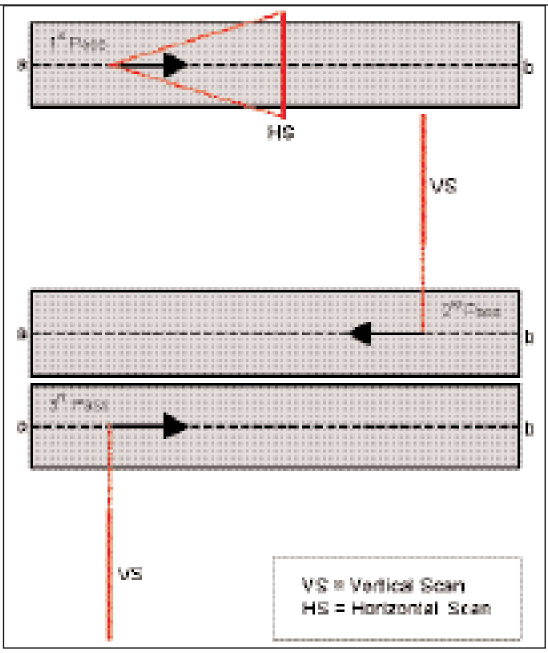
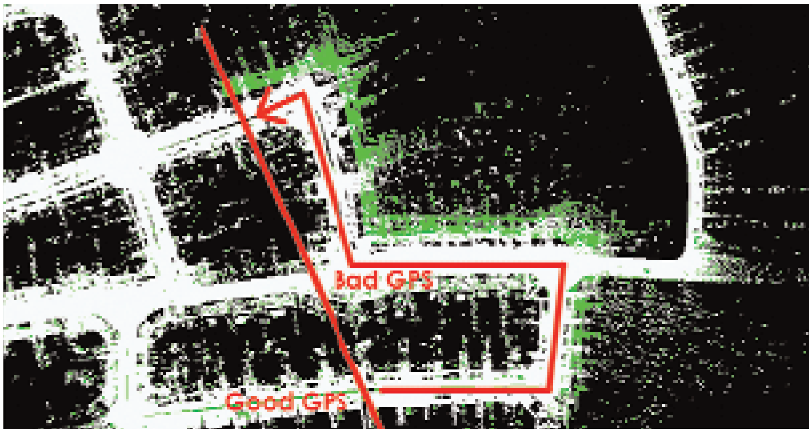


FIGURE 4 Simplified representation of three-pass approach



▲ **FIGURE 5** depicts the processed point-clouds associated with a post-Afghanistan urban project where numerous cycle slips occurred. In the absence of GPS, the GPS/IMU solution drifts with time as shown by the green point cloud. Further optimization of the processing algorithms and methodologies allows for full recovery of drift-free trajectories, as depicted by the white point cloud.

The Afghanistan survey proved that the SideSwipe system could provide production data acquisition, but realistically it is necessary to place more weight on the IMU contribution to the positioning solution when surveying in most environments. After Afghanistan, our next SideSwipe project took place in an urban environment with all the obstructions one would normally expect. In this case it was necessary to further develop the solution so that the IMU would supplement the GPS during periods when the system suffered many cycle slips for extended periods (see **Figure 5**).

Reopening the Highway

In December 2003, officials reopened Phase I of the highway, from Kabul to Kandahar, reducing travel time from two days to five hours. Designed to withstand traffic for 15 years, the asphalt can accommodate vehicle speeds of up to 100 kilometers per hour. The $190-million reconstruction, that employed 1,500 Afghans, now provides better access to markets, health care, education, and jobs. Businesses benefit from the increased ease of trade that contributes to the recovery of the Afghan economy.

Shortly after the Phase I, the Terrapoint team completed the Phase II survey from Kandahar to Herat. In Phase I, traditional land-based techniques surveyed in excess of 400 kilometers in 200 days. By comparison, Terrapoint completed 566 kilometers of surveying using the SideSwipe system in 45 days, a 629 percent increase in efficiency.

▼ **LOCAL AFGHANS** observe paving of the Kabul–Kandahar Road.

Moving Forward

As Phase II continues, construction crews are making further improvements to the road from Kabul to Kandahar: additional layers of asphalt laid, highway shoulders improved, and additional signage introduced. Construction work on the Kandahar–Herat highway, now under way, should conclude in 2006.

The SideSwipe system, with conversion to truck from helicopter in half a day and operation costs at a fraction of those for a helicopter-based system, offers superior flexibility. With this ground-based system, the continuous operation offered by the GPS/IMU system assumes even more importance, as GPS outages created by bridges, large buildings, or heavy foliage may be more prevalent. Engineers at Terrapoint are currently integrating the manufacturer's newly introduced GPS/IMU solution into their LiDAR design and continue to find unique applications and environments that benefit from the versatility of the SideSwipe system. ⊕

SIMON NEWBY received a B.Sc. in Surveying and Mapping from North East London Polytechnic, followed by an M.Sc.E. in Surveying Engineering from Canada's University of New Brunswick. He has worked with various facets of GPS technology and its applications since 1985. Since joining Terrapoint in 2003, he has turned his attention to integrated positioning technologies (LiDAR in particular) and their use in a variety of mapping applications.

PAUL MRSTIK co-founded Terrapoint (formerly Mosaic Mapping Systems Inc.), which was acquired by Pulse Data Inc. of Calgary, Alberta, Canada, in 2004. An electronics engineer with a broad range of mapping and data acquisition experience spanning 30 years in operations, software development, and engineering, he led the development team that created a LiDAR and digital imaging system that operates in the air, on land, and from the water.

Manufacturers

Components used for data acquisition included a **Riegl** (Horn, Austria) laser scanner and a high resolution **Sony** (Tokyo, Japan) video camera. Video imagery was logged via FireWire to *Kronos* video logging software by **Geo–3D Inc.** (St. Hubert, Quebec, Canada). The GPS/IMU system used during the Afghanistan survey integrates **NovAtel's** (Calgary, Alberta, Canada) *Black Diamond System (BDS)* and the *HG1700* IMU from **Honeywell Defense & Space Electronic Systems** (Clearwater, Florida). The GPS/IMU system currently integrates NovAtel's *SPAN* technology with a *DL-4plus* receiver.