Coastal Area Tactical-mapping System (CATS)

Ramesh L. Shrestha
University of Florida
Department of Civil & Coastal Engineering
Gainesville, FL 32611
phone: (352) 392-4999    fax: (352) 392-5032    email: rshre@ce.ufl.edu

K. Clint Slatton
University of Florida
Departments of Electrical & Computer Engineering and Civil & Coastal Engineering
Gainesville, FL 32611
phone: (352) 392-0634    fax: (352) 392-0044    email: slatton@ece.ufl.edu

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LONG-TERM GOALS

The long-term goals of the CATS project are:

1) to improve detection and identification of anti-vehicle and anti-personnel obstacles and munitions in the coastal zone, and
2) to gain a fundamental understanding of the low-energy lidar phenomenology of the earth’s surface, near-shore coastal environments, and vegetation foliage.

OBJECTIVES

The overarching objective of the CATS project is to design, build, and demonstrate a low-power scanning airborne laser altimeter capable of continuous ground coverage, superior three-dimensional (3D) sampling, and shallow-water penetration.

APPROACH

The technical approach we have taken to achieve the stated objectives and goals is to employ multi-channel photon-counting technology. This technology allows the use of low-power, low-weight micro lasers with much shorter pulse lengths than traditional airborne laser swath mapping (ALSM) lidar systems (e.g. 480 picoseconds for CATS versus 10 nanoseconds for an Optech, Inc. 1233). The short pulse length allows comparable range resolution to traditional ALSM without the need for constant-fraction based detection of the return photon packet. This in turn allows the use of detector electronics that are well suited for recording large numbers of return events per pulse rather than just a few discrete returns. Recording additional returns per pulse leads to a more nearly 3D representation of terrain, foliage, and targets, as well as greater penetration of diffuse objects, such as netting. The key individuals participating in this work are listed in Table 1.

Table 1: Key individuals participating in CATS and their roles
<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramesh Shrestha</td>
<td>UF</td>
<td>PI: Programmatic, fiscal</td>
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<tr>
<td>Clint Slatton</td>
<td>UF</td>
<td>Co-I: Design, sensor modeling</td>
</tr>
<tr>
<td>Bill Carter</td>
<td>UF</td>
<td>Design, systems engineering, oversight of integration and testing</td>
</tr>
<tr>
<td>John Degnan</td>
<td>Sigma Space, Inc.</td>
<td>Detailed design of optical-mechanical and laser subsystems, system-level integration</td>
</tr>
<tr>
<td>Bill Gavert</td>
<td>Fibertek, Inc.</td>
<td>Detailed design and testing of receiver subsystem</td>
</tr>
<tr>
<td>Joe Foster(^1)</td>
<td>Dynetics, Inc.</td>
<td>Target phenomenology and environment simulation</td>
</tr>
</tbody>
</table>

**WORK COMPLETED**

**System integration:**
The major components of the CATS system, including the micro-laser, holographic element, Risley scanner and driver assembly, internal communication electronics, photomultiplier tube (PMT) detector assembly, and data capture electronics were fully integrated by Sigma Space Inc. and Fibertek, Inc. in early 2006. During integration, bench testing of the various components occurred. On one occasion, the PMT was inadvertently illuminated with backscattered laser light at close range by Sigma Space personnel, but subsequent tests of the PMT indicated that no significant damage to the PMT occurred.

**Ground-based testing:**
Since integration, the CATS system has undergone rooftop testing at the Sigma Space facility in Lanham, MD three times with personnel from Sigma Space, Fibertek, and the University of Florida (UF) present. The tests took place on: (1) March 2, 2006, (2) May 26, 2006, and (3) July 21, 2006. These tests took place on top of a 4-story building. The laser sensor was pointed at buildings, the ground, and vegetation 200-800 m in the far field, and range data was collected during short scans for testing purposes. The tests successfully verified the outgoing beam pattern and gross pointing accuracy, the scanner operation, the PMT signal pathway to the data capture electronics, and the ability of technicians to adjust the gain levels on the individual PMT channels.

At the current time, multiple issues uncovered during the tests still remain unresolved, such as anomalous range readings or dropped data on some laser shots, non-uniform PMT channel sensitivity, and time tagging errors. All of these issues appear to be resolvable with straightforward engineering solutions. The primary impediment to completion of CATS and the collection of airborne data has been the limited availability of Sigma and Fibertek personnel due to their obligations on other projects. This lack of personnel availability has significantly slowed progress on the CATS testing. As a result, UF requested, and was granted, a no-cost extension from ONR through March, 2007. In addition, UF has re-targeted some of the funds and allocated internal funds (non-ONR funds) to support additional work by Fibertek and Sigma to complete the CATS system.

**RESULTS**

The software for processing raw range files output by the Fibertek electronics was initially developed in Matlab by UF, but the size of the continually evolving output data prompted several revisions to reduce CPU processing time. While some measures were taken to speed up the Matlab algorithms, the resulting code was eventually ported to C++ by UF for better utilization of CPU cycles. The newly

\(^1\) Field testing will not be performed by Dynetics as originally planned because the system is still undergoing testing at the Fibertek and Sigma facilities. UF personnel will conduct field testing when the system is ready.
converted application performs the same operations approximately one thousand times faster than Matlab version. The code is written such that ascii file outputs are easily imported back into Matlab for quick manipulation into graphical plots.

Fibertek made several changes to the binary file (*.SPR) output structure to support the inclusion of a fifth data field for time tags. Additions to the processing code were subsequently necessary in order to accommodate the altered data stream. The base code functions remained intact in regard to the initial objective of characterizing information about each potential return related to the following values: (1) shot number, (2) channel number, (3) hit number, (4) range information.

After code additions, the next step was to verify the time tag output content. The converted output from two 32-bit words described by Fibertek documents matched with the per-shot time tag information displayed in the new version of Fibertek’s custom-built data processing software, SPRView. This confirmed that UF’s software was correctly interpreting the new binary stream. It should be noted that a major goal of including time tag information for both laser shots and scanner index marks is to reconcile the position of the scanner at any given time in relation to the sequence of laser pulses in a data set. Incorporating this new data field allows for analysis of potential data flow problems, e.g. if the laser fire slaving system happens to miss any pulses or the scanner malfunctions. Once correctly implemented, time tag information will greatly aid in post-processing and potential troubleshooting.

Timing Issues
Attempting to synchronize the laser shot time tags to the scanner index mark time tags from the test data sets exposed errors in the time tag outputs. Erroneous time tags were generated on many laser shots. For example, shots occurring later in the firing sequence displayed tags which report earlier GPS times, and some tags display in hex rather than decimal. Because the conversion of GPS time tags from the binary to ascii data was independently verified, the discrepancy is thought to occur in the generation of the time tag itself rather than in the conversion of the raw file.

Further testing at Fibertek revealed that the 100 Hz time data was not being cleared before each laser shot. More investigation showed that the CPU used to process the incoming data stream was being overloaded due to the data throughput. Because of this, the laptop was unable to keep up with the incoming range data and the 100 Hz time data buffer would periodically overflow. Possible solutions to the timing issues were discussed by UF and Fibertek personnel. A suspected bug in the way that the microsecond value was being updated from the GPS will be addressed so that the counter is properly cleared for each GPS time tag.

Ranging Issues
Two initial rooftop tests in 2006 were simply intended to verify the basic functioning of the integrated CATS unit, such as scanner motion, outgoing laser pulses, and received signal detection. For the first two tests, the scan angle readout and GPS time tags were not available, and the PMT channel thresholds were intentionally set high to protect the PMT from any unpredicted high-energy returns. Thus, it was not possible to form precise 3D point clouds of the lidar returns from those tests, although approximate 3D points clouds were formed by assuming a nominal laser fire rate. Basic signal detection at the PMT while the scanner was in motion was verified at both cold and mild ambient outside temperatures.
In July of 2006, a third rooftop test was performed. During this test, the ambient temperature on the roof was hotter than nominal operating conditions (at or above 90° F during the day). Fluctuations in the laser pulse repetition frequency were observed from data collected at that time, resulting in problems with misaligned range gates, which are triggered by the laser pulse signal. However, subsequent testing at night resulted in better data sets.

- During the nighttime tests, when the Risley scanner was set to the zero-deflection setting (opposing prism wedges set 180° out of phase and stationary), it was possible to see the stationary laser footprint on a building face approximately 265m from the CATS sensor. In Fig. 1, photographs of the laser footprint are shown. By noting the footprint location we were able to verify that the outgoing beam was pointing in the desired direction, i.e. the scanner optics housing was properly aligned with the sensor frame. We were also able to measure the size and separation distance of the beamlets to confirm that the holographic element was properly focusing the outgoing laser energy.

- Due to the cooler nighttime temperatures, the laser pulse rate stabilized closer to the nominal 8 kHz, which in turn helped the range gate alignment and so improved the precision of the recorded ranges. In Figure 2, the recorded ranges are plotted, and relevant statistics from one of the nighttime tests are given. Six of the total 96 active PMT channels recorded negligible or zero returns throughout the testing. These channels are not restricted to a particular region of the PMT or to a particular data capture board. So it is believed that they are either not functioning at all or have had the detection thresholds erroneously set too high. The remaining 90 out of the 96 active PMT channels recorded very uniform ranges. For the returns shown in Fig. 2, a precise range gate of 264m – 266m was used in post processing to reject returns from atmospheric haze once the approximate target range of 265m was determined. The precise mean range to the footprint on the building face was determined to be 265.12 m with a standard deviation of approximately 7.5 cm. These range values were considerably more uniform than those obtained during the hot daytime testing.

- There is still a greater than expected variation across the PMT channels in terms of the number of return events. This can be seen in the top plot of Fig. 2, where total return events per channel range from just under 30,000 down to about 1,000 for approximately 2 seconds of data, neglecting the 6 channels with no returns at all. Some of this channel-to-channel variation is due to the unequal reflectances of the brick and mortar on the illuminated wall in Fig. 1. Some of the beamlets fell only on brick, some fell directly on mortar seams or mortar seam intersections, while others had a small fraction of mortar in their footprints. In Figure 3, the correspondence between PMT channels, data capture boards, and return counts is shown. UF and Fibertek personnel believe that the PMT is slightly out of alignment with the return optical path, such that the column of channels on the right edge and the row of channels on the bottom edge are minimally illuminated. The return counts in those channels are thus reduced but still measurable.

Planned activities
A new contract using UF internal funds is planned for Fibertek to address these remaining issues. Additional rooftop testing will subsequently be carried out to verify the Fibertek fixes. Then installation in the UF aircraft and airborne testing will occur prior to March 2007.

IMPACT/APPLICATIONS

The successful operation of the CATS sensor, especially over surfaces covered by shallow water or vegetation, will demonstrate a dramatic improvement over traditional surficial lidar mapping, while
using a lower-weight, lower-power approach suitable for Unmanned Aerial Vehicles (UAVs). It thus has the potential to revolutionize the field of high-resolution topographic mapping.

Two presentations on CATS were made at international conferences this past year. The first was a poster by Dr. William Carter (of UF) at the Fall Meeting of the American Geophysical Union (AGU) in San Francisco, CA, entitled, “Geodetic Laser Scanning: Refractive Optics Offer Wide Variety of Scan Patterns”. The second was by Dr. John Degnan (of Sigma Space) at the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) in Denver, CO, entitled, “Second-Generation, Scanning, 3D Imaging Lidars Based on Photon-Counting”. Co-I Slatton organized and co-chaired the session in which Dr. Degnan gave his talk. The session was entitled, “Lidar: Information Extraction and Applications”. Also, Dr. William Carter was lead author on the paper "Risley Prisms: 125 Years of New Applications", W. E. Carter and M. S. Carter, Eos – Transactions Geophysical Union, vol 87, no. 28, Pages 273, 276, 11 July 2006.

TRANSITIONS

The CATS sensor will be of significant interest to researchers supported by the National Science Foundation (NSF) because of the potential for dramatically improved topographic mapping, including mapping the bottoms of shallow streams and lakes. The ability to extend beach surveys below the water line to depths of a few meters is also of great interest to coastal engineers and agencies such as the Florida Department of Environmental Protection.

RELATED PROJECTS

1. Sponsor: National Science Foundation. Title: The National Center for Airborne Laser Mapping (NCALM). NCALM helps to maintain and improve infrastructure at UF for collecting and processing ALSM data. The CATS sensor head will be mounted into the UF Cessna 337 aircraft used for most NCALM acquisitions. The existing GPS and IMU system in that aircraft will also be used for CATS. See http://www.ncalm.ufl.edu/ for more information.
3. Sponsor: Harris Corporation. Title: Improved Segmentation of Buildings and Vegetation in Airborne and Ground-Based Lidar. A one-year project to collaborate with Harris Corporation for developing methods to extract buildings and infrastructure from 3D lidar point clouds.
Fig. 1: The laser footprint visible on the side of a building near the Sigma Space facility during nighttime testing. The overall beam divergence and the divergence and positioning of the 10×10 beamlets created by passing the beam through a holographic element was confirmed to be close to the design specifications. The building was approximately 265m from the sensor.

**Statistics:**
- number of shots fired: 16000
- total number of hits in file1: 1279197
- number of channel error hits: 0
- number of non-error hits: 1279197
- total number of filtered hits: 922202
  (72% of total)
- average hits per shot for all hits: 79.95
- average hits per shot for filtered data: 57.64
- averaged range to target, all channels: 265.12 m
- standard deviation of target range: ~7.5 cm

Fig. 2: Return event counts recorded over approximately 2 seconds, during which time the laser was illuminating the brick wall shown in Fig. 1 at a range of 265m. Six channels effectively registered no returns at all. The range precision is quite good, with a standard deviation of approximately 7.5cm. However, there is significant non-uniformity in the return event counts, suggesting heterogeneous gains across the PMT channels. It should be noted, that some of the return count variability is attributable to the different reflectances of the brick and mortar on the illuminated surface in Fig. 1.
Fig. 3: (Left) The Hamamatsu Electronics Inc. model R4110U-74-M100D PMT used in CATS. (Right) a front-view diagram of the PMT in which the correspondence of channels to each of the 6 data capture boards is indicated, along with the return event counts for approximately 2 seconds of illumination of the brick wall in Fig. 1. In general, most of the low-return channels are near the right edge and bottom edge, suggesting a slight misalignment of the PMT with the optical path.