Title of Investigation:

PN Code Modulated Fiber Lasers for Push-broom Mapping Altimetry from Orbit

Principal Investigator:

Dr. James B. Abshire (Code 690.5)

Other In-house Members of the Team:

Dr. Michael Krainak (Code 554), Dr. Xiaoli Sun (Code 694), and
Dr. David Harding (Code 698)

Other External Collaborators:

None

Initiation Year:

FY 2004

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

$61,000

Funding Authorized for FY 2005:

$36,000

Actual or Expected Expenditure of FY 2005 Funding:

In house: Components, $20,000; Mechanical lab support, $6,000; and programming support, $10,000

Status of Investigation at End of FY 2005:

This phase (exploration) completed in December 2005. Next phase will be transitioned to RT. The follow-on work has been funded under the NASA Earth Science Technology Office's (ESTO) Instrument Incubator (IIP) program

Expected Completion Date:

December 2005

Purpose of Investigation:

Currently, satellite-based laser altimeters measure the height of ice sheets, land topography, and trees along a single profiling line. However, many more science questions can be answered if the altimeter can measure surface-height distributions in a broader mapping swath, which is comprised of many smaller individual footprints. Several areas of geophysics will significantly benefit if one can develop laser altimeters to make full 3-dimensional maps of surface height from orbit with measurement spots of 5–10 m and swath widths of greater than 200 m.

This work has investigated the feasibility of a measurement approach that collects data along many profiling tracks in parallel. It has no moving parts and uses a new type of laser (fiber lasers) as the transmitter. The results have been very encouraging. The approach appears practical for space missions, both in the near term and for higher capability ones in the future.

Mapping measurements of land topography and vegetation structure are now made routinely from aircraft carrying scanning laser altimeters. These use low-energy lasers, which are pulsed at KHz rates and which are mechanically scanned to permit cross track (sideways) coverage. However, there are significant challenges in moving this capability into space, including orders-of-magnitude weaker signal, faster measurement speeds, and the need for much longer laser lifetimes.

Our work has investigated a new way to meet the space measurement needs, using a fiber laser-based altimetry configured into a novel swath-mapping "push-broom laser altimeter." A passive push-broom sensor for a satellite uses an array of passive sensor elements, which view a planet's surface across the orbital track. The orbital motion of the satellite then "pushes" the sensor-measurement line along the ground track of the satellite, like a broom sweeping across a floor.

We adapted the push-broom measurement strategy for the first time to active laser-altimeter measurements, as is shown in Figure 1. The approach uses identical small low-energy, high-pulse rate lasers, with sensitive photon-counting detectors in its focal plane for each line of the push-broom swath. The detectors share a common receiver telescope. The lasers and detectors are replicated cross track, as is shown in Figure 2, to achieve a push-broom swath and coverage without scanning. Our work has shown that this approach is very flexible, robust, and enables accurate laser altimetry from orbit.

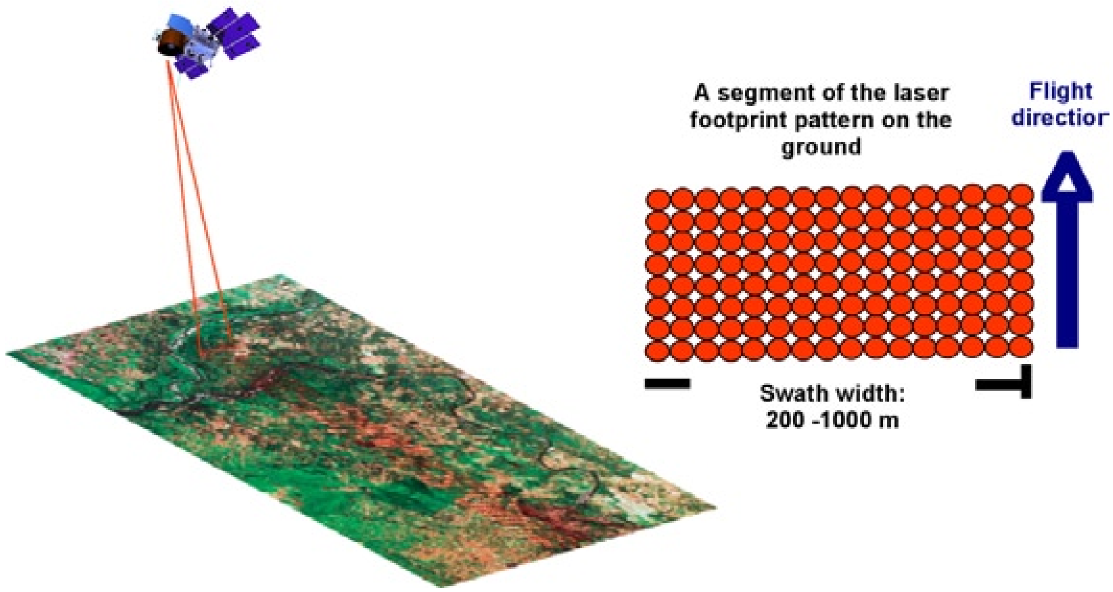

Figure 1. Swath-mapping laser altimeter concept and the laser spot pattern on the ground in the mapping swath. The technique measures the surface height distribution within each 5- to 10-m diameter laser spot.

Approach:

In our approach, each fiber laser and photon-counting detector pair forms one line of the "altimeter pushbroom," a 5- to 10-meter-wide laser-profiling track. By using many of these pairs displaced in a line across the track, altimetry measurements can be made simultaneously over a wide push-broom swath. This approach is flexible, and the width of the track is scalable from ~200 m to over 1 km, depending on the coverage needed and the mass and power available for the payload. Other advantages are: 1) higher-spatial and vertical resolution; 2) the architecture is parallel and scales to very wide swaths; 3) much-higher power and photon efficiency; 4) the laser technology is based on a strong growing industrial base; 5) it allows redundancy and fault tolerance. The lasers and detectors can be redundant, and failure of a single laser or detector only drops a single measurement line; and 6) it is flexible in measurement format. Both the laser-modulation format and receiver integration time can be changed on-orbit to optimize measurement performance for different Earth surface types.

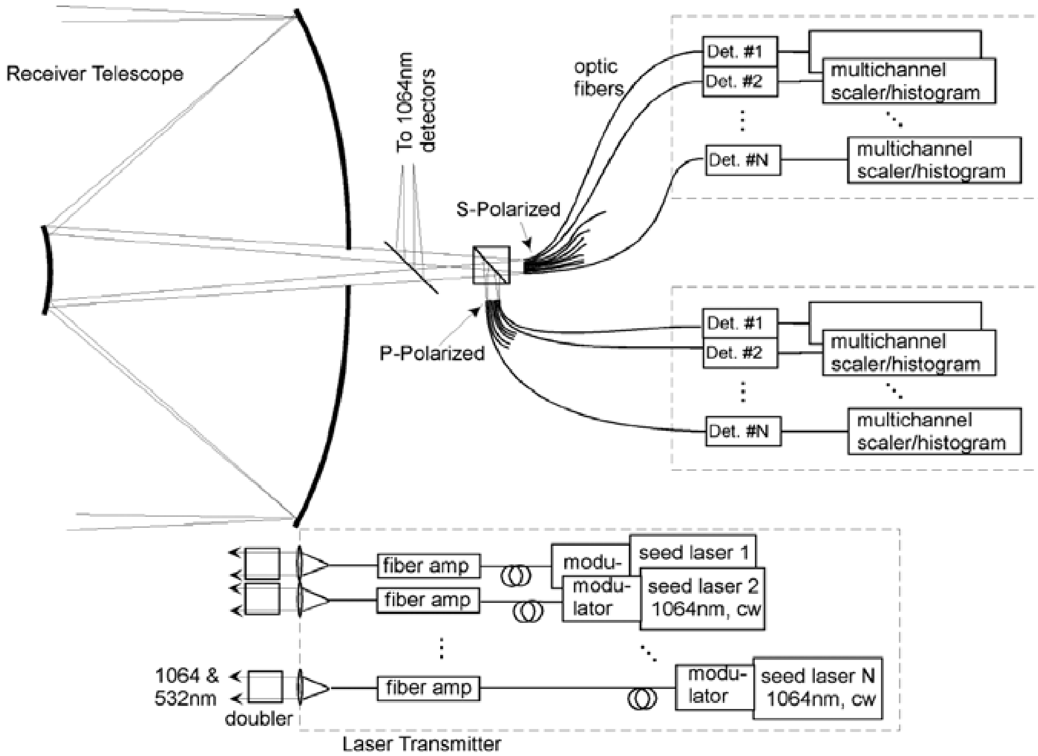

Figure 2. One possible swath-mapping laser altimeter instrument configuration

A key capability needed is a laser measurement technique, which allows for efficient and reliable measurements along a single profiling line. We focused our DDF work on this area. We chose a modular technique based on fiber-laser technology, digital modulation, and photon-counting detectors. Our transmitter is seeded with a diode laser externally modulated by a digital-ranging code and scaled to Watt-levels by a fiber amplifier.

Fiber amplifiers are attractive for space use for many reasons, and some of these are summarized in Figure 3. Lucent Technologies has developed fiber lasers for defense applications and has done extensive development on long lifetime (> 15 year) fiber-laser components for undersea fiber-optic cables. Photon-counting detectors have low time jitter and are much more sensitive than the analog detectors, which have been flown on laser-altimetry missions to date.

Fiber amplifier characteristics:

Light stays in waveguides
Inherently rugged
In production by a growing industrial base
Very reliable pump laser diodes; several suppliers
Distributed thermal load
Low parts count
Wide wavelength range available
Single frequency laser diode seed sources available
Scalable to high powers
High wall-plug efficiency, > 15% (Yb)
Active R&D area in industry & universities
Compatible with micropulse & pulse code modulations

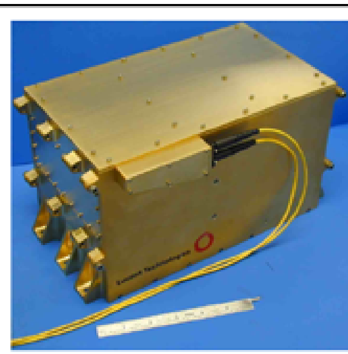

Figure 3. Characteristics of seeded-fiber amplifiers and an example of a fiber amplifier from Lucent Technologies.

Laser-altimetry measurements require high-bandwidth laser modulation, and we have examined two different types for this application. In the high-rate, low-peak power approach, shown in Figure 4, the fiber laser's output is optically modulated at about 1 Gbit/second rate by a PN Code. This code impresses a digital-ranging pattern (with 50% duty cycle) on the power of the optical carrier. The delay of the ranging code (and thus the range) can be unambiguously recovered in the receiver-to-yield range measurements with better than 2-cm precision. This is done by first time sorting and accumulating (i.e. histogramming) the detected photon counts into range bins corresponding to positions in the transmitted code, and then after integration, by cross correlating the accumulated photon histogram against the transmitted code. For example, 1.5 ms integration time can be used to obtain 700-Hz measurement rate for 10 m along track resolution.

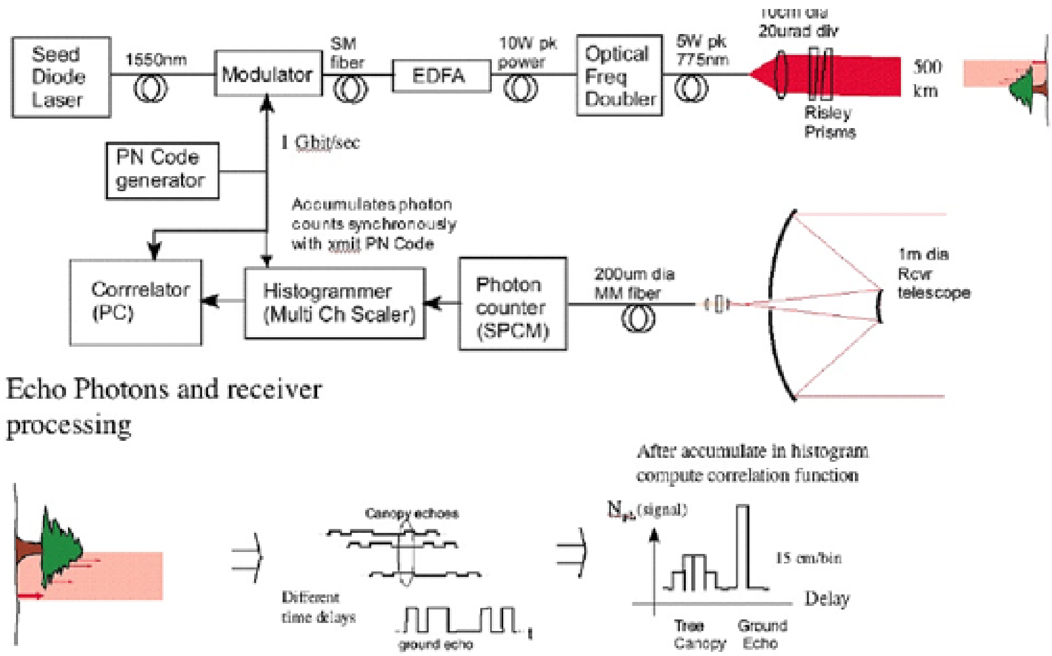

Figure 4. Block diagram of a single-measurement channel for a push-broom laser altimeter, which uses pseudo-noise modulation and photon-counting detection. A common receiver telescope is used with many of these measurement channels in parallel (i.e., with their measurements distributed cross-track). Each laser/detector/histogram subsystem forms one measurement line of the measurement swath.

The other approach is similar to "micropulse" lidar and laser altimeters. It uses a more conventional short pulse laser-measurement technique, and many small energy pulses for each measurement. This approach, which is shown in Figure 5, uses narrow (~1 ns wide) pulsed lasers, which have kilowatt peak powers and low (<1%) duty cycles. In this case, the photon-counting histograms at the receiver directly yield the range distribution to the surface. Both the PN and micropulse technique are compatible with fiber lasers. The fiber lasers appear to be the best choice for a wider swath-width instrument for a mission in the future. A microchip laser-based instrument also seems practical for space now.

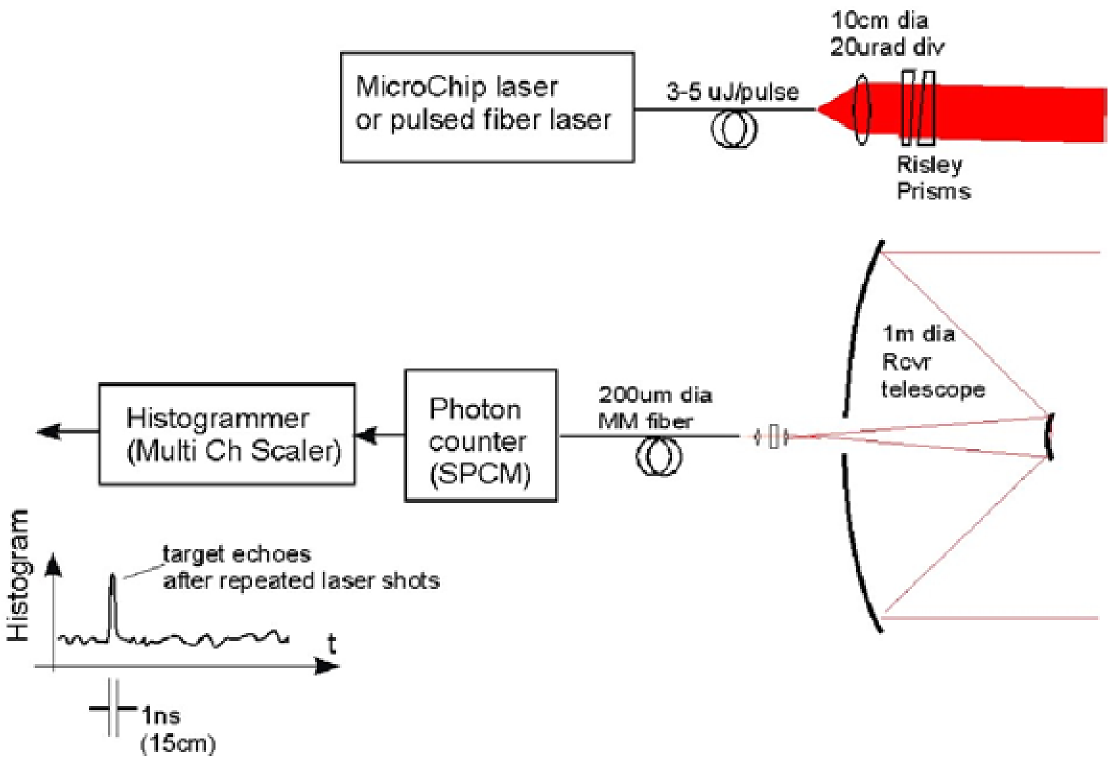

Figure 5. Micropulse laser measurement approach. It measures the surface height with many low-energy nanosecond-width laser pulses and photon-counting detectors. It is also flexible and can use: Nd:YAG microchip lasers or high-rate pulsed fiber lasers. The technique and its Nd:YAG laser components are mature and have high technical readiness level.

Accomplishments to Date:

We have made excellent progress and our overall approach appears very promising for space laser-altimeter opportunities. Most of our work focused on developing and demonstrating the needed measurements and addressing scaling to space. In parallel, we also organized work on a related Earth-mapping mission concept called DELI. We convened workshops and collected and compiled similar requirements for high-spatial resolution, space-lidar measurements for ice-sheet topography, topography, vegetation-height mapping, and hydrology science areas. This mapping approach seems the best candidate for DELI.

The approach also is flexible in measurement wavelengths. We calculated the performance of this technique for fiber amplifiers and detectors operating at 1060, 770, and 532 nm. The comparisons highlight trading higher laser efficiency at 1060 nm, compared with improvements in detector efficiency and maturity at 770 and 532 nm. Although the system specifications are different, these wavelengths all appear viable.

For the laboratory work, we assembled the key hardware items and assembled them in our laboratory in Building 33, as shown in Figure 6. We demonstrated amplification of the PN-encoded, intensity-modulated seed lasers at 100- and 250-MHz rates by a fiber amplifier at 1570 nm. We have demonstrated PN-coded ranging using a fiber-laser transmitter at 1570 nm and a photon-counting detector at the receiver. These measurements were made to a tree trunk over the 206-m long horizontal path shown in Figure 7.

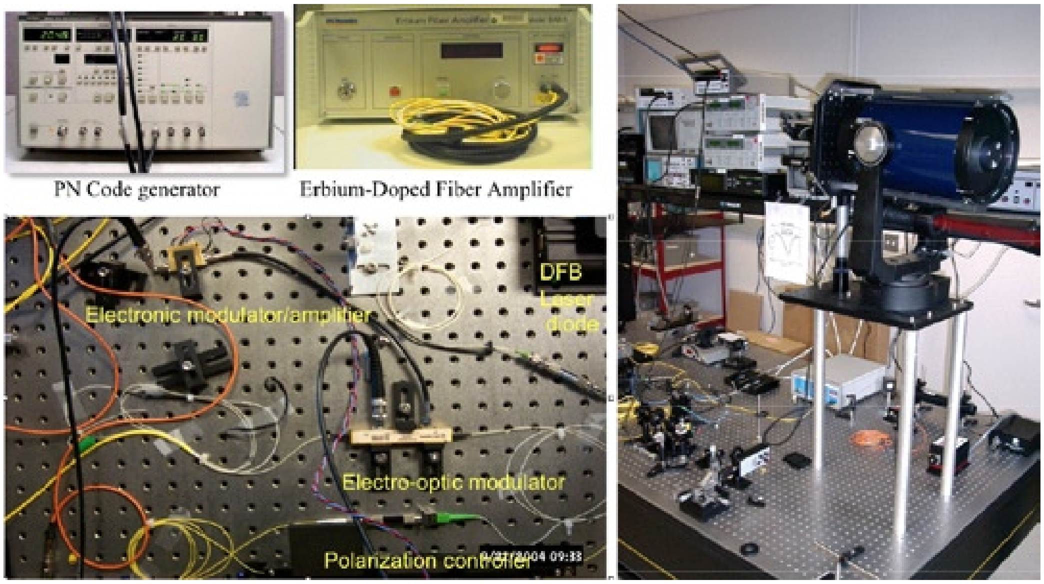

Figure 6. Photo shows the laboratory breadboard setup. Initial experiments were at 1570 nm, utilizing components from prior work. The telescope is aimed at a target, located out the window, across the test path.

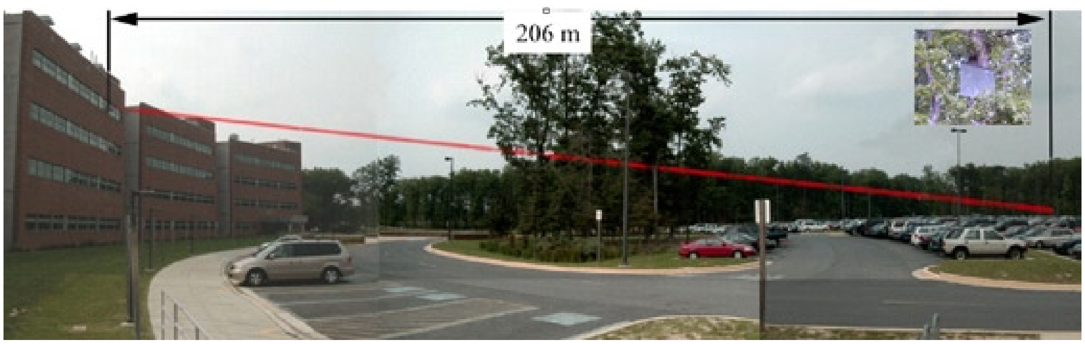

Figure 7. Our measurement test path above the parking lot outside B33. The red line is a sketch of the approximate beam line and not the actual laser beam, which is eye-safe and 4 m or higher above the ground.

Our experiments verified the measurement performance of the PN-Code technique. We used a transmitter with a stable single-frequency seed laser, whose output is intensity modulated by a digital PN sequence. This signal is amplified by a fiber amplifier and collimated. The photons scattered from the surface are collected by the receiver telescope and passed through a band-pass filter to illuminate a photon-counting detector. The resulting counts were accumulated (histogrammed) synchronously with the transmitted code. After about 1 ms integration time, the histogram is cross-correlated with the transmit code to yield the backscatter versus range profile (i.e., the altimeter echo waveform). If the code and histogram use a 1 Gbit/s modulation rate, the resolution of the echo waveform will be 15 cm/bin.

An initial experiment used a single-frequency, 1570-nm diode laser, whose output is modulated by an external modulator with a 127-bit PN Code at 100 Mbits/second, amplified by a fiber amplifier to about 1 W of optical power, then transmitted over the horizontal path to a cooperative target. The backscatter was collected with a 20-cm diameter telescope and the echo signal detected with an analog detector. The signal was digitized and the waveform was cross-correlated with the transmitted code. The measurements are shown in Figure 8. The cross correlation plot shows the well-defined round-trip correlation peak at 412 m for the one-way distance of 206 m.

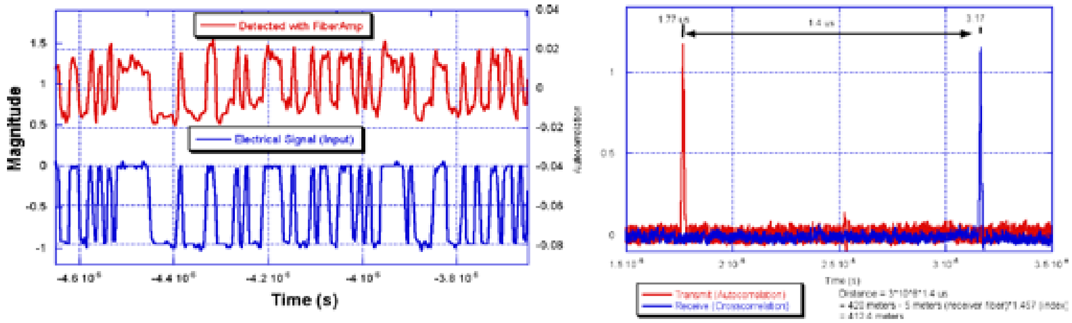

Figure 8. Transmit and time-shifted return echo using a 100 Mbit/s PN-coded seeded laser, amplified and an analog detector. The cross-correlation peaks (right) correspond to the round-trip travel time to the target at 206 m.

We explored the detection performance at low-signal levels in a laboratory experiment. For it, we modulated only the diode laser signal, which was then attenuated and fiber coupled into an infrared photon-counting PMT detector. For these experiments, the detected signal count rate was about 120 kHz, and the background only count rate was about 100 kHz. The results, shown in Figure 9, indicate that the technique can measure at low-signal levels and the high rates (700 Hz) needed from space. It also shows the measurement statistics scale with signal as expected.

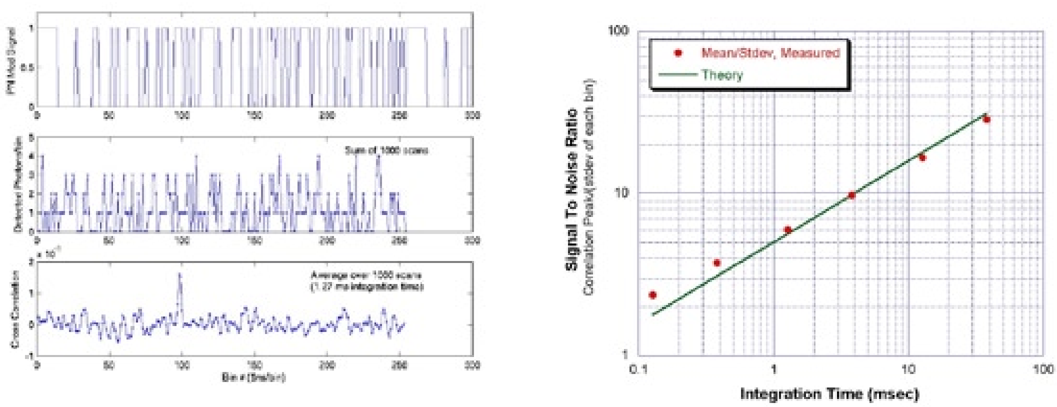

Figure 9. Results from laboratory photon-counting experiments. (Left, from top to bottom) Reference PN waveform, detected photon-counting histogram accumulated in 1.27-ms integration time and the cross correlation, which clearly shows the expected range spike with an offset of about 100 range bins. Right: the signal to noise ratio (SNR) as function of receiver (i.e., histogram) integration time. The SNR of the correlation peak varies as (integration time) 1/2 as expected. Based on theory, an SNR of ~6 is needed for 99% detection probability, which required 1.2-ms integration time.

We further tested the timing and SNR performance of this system using 250 MHz PN-Code modulation, using a 250-ps resolution timer to register the photon-arrival times. The results are shown in Figure 10. They show the range delay, SNR, and probability of detection all scale with signal as expected from theory. Received signals with a few pW power are sufficient for reliable measurements. The measurements are unbiased and with 4 pW received power the range jitter is <3 cm. Measurements made over the horizontal path to a tree trunk show the strong correlation peak and the expected triangular shape.

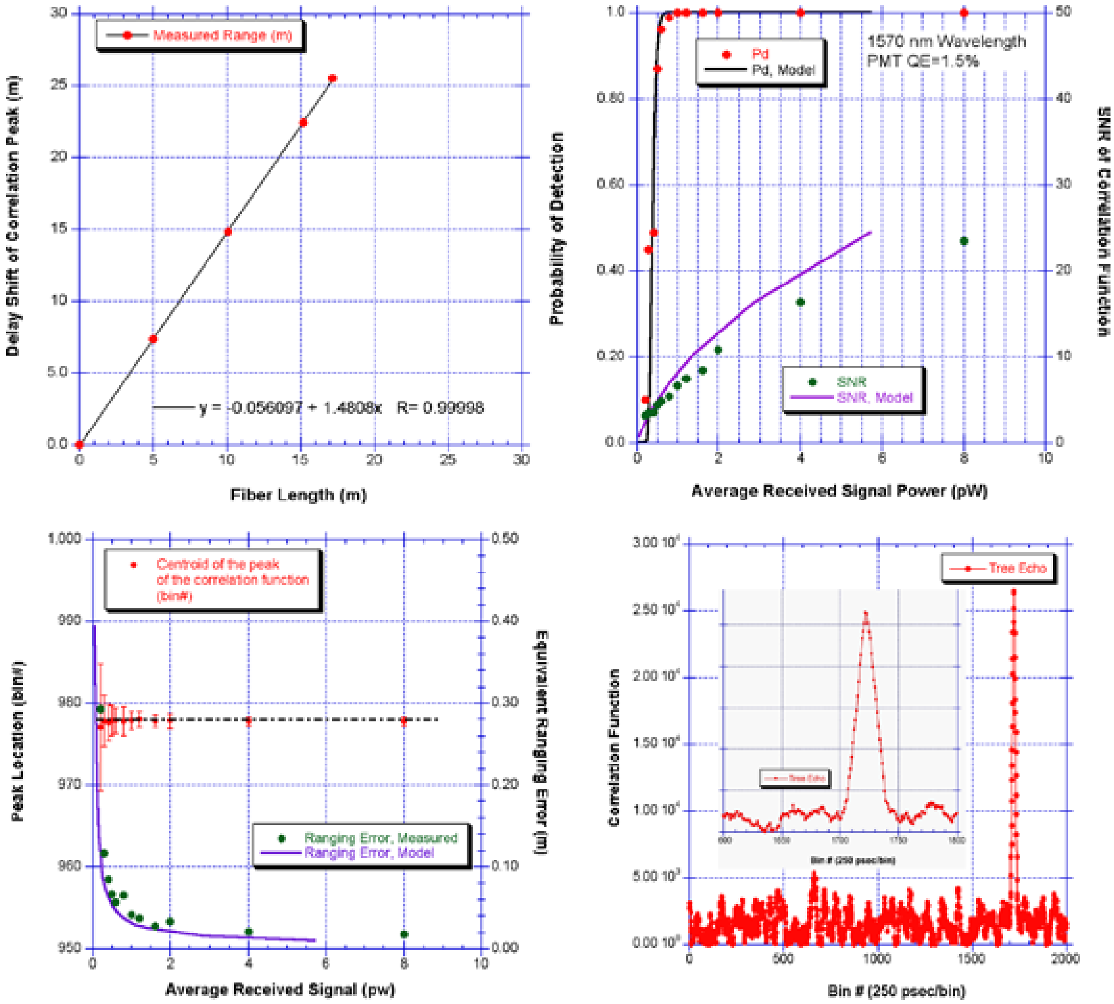

Figure 10. Results of testing PN-Code modulation in laboratory with the photon-counting PMT detector. The tests were performed at 1570 nm, using 250 Mbits/second modulation, and a 1 ms receiver integration time. Top left—Tests with different length fiber cable delays. Top right—SNR and probability of detection versus signal level. Bottom left—Range bias and error versus signal level. Bottom right—Impulse response of side of tree trunk (lower right) measured over the horizontal test path. The inset shows an expanded view of the correlation.

Our results from testing the micropulse-measurement technique in the laboratory are shown in Figure 11. These used a Nd:YAG microchip laser and a SPCM photon-counting detector, like those used in the GLAS 532-nm receiver. The results show that the single photon-timing distribution has the expected ~1 ns width. They also show that this approach is essentially unbiased in range of detection probabilities < 0.2. This is practical since it requires ~1 μJ laser energy/pulse from space. High-detection probabilities and SNRs can be achieved (i.e., accumulated) by using multiple laser firings per laser spot.

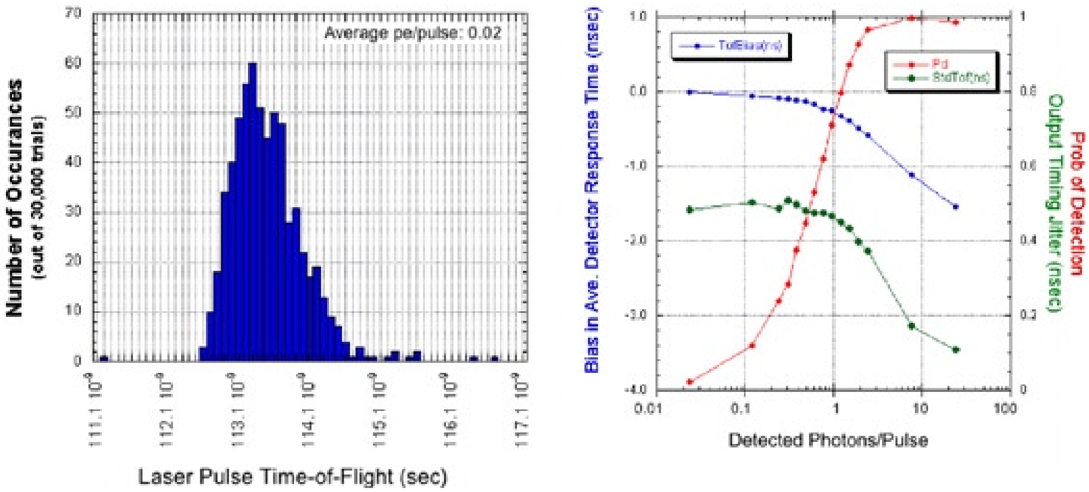

Figure 11. Laboratory tests of the micropulse measurement technique. Left - The photon-counting histogram at low signal levels. Right—Plots of the bias in the measurement (in blue) the probability of detection (in red) and the output timing jitter (in green). The results show for biases < 2 cm the detection probability should be <0.2.

We also prepared numerical models and calculated the performance of candidate altimeters that use modulated lasers and a photon-counting detectors. Some results from calculations are shown in Figure 12. These were based on a 500-km orbit, 70% atmospheric transmission, and 10-m diameter laser spots on an ice surface with 3˚ slope. The altimeter was assumed to use a Yb-fiber amplifier at 1060 nm, a 1-m diameter receiver telescope, and a 5% quantum efficiency photo-multiplier (PMT) detector with 1 kHz background rate. The receiver integrates for 1.5 milliseconds per measurement and the uncertainty height interval is 1.5 km. Plots are shown both for a 4% duty cycle micropulse technique and a 50% duty cycle PN Code at 500 MHz modulation rate. The detection probability and range errors are shown for day and night. For these examples, detection probabilities of greater than 90% and ranging error of <10 cm at a 700 Hz rate can be attained with about 0.6 and 3 W average laser power.

Given the number of parallel channels in a swath-mapping altimeter, the energy needed by the laser per measurement in the swath is important. Our results to date show that the fiber laser-based swath-mapping altimeter can improve the power efficiency by 20 to 100 times compared with an improved version of the GLAS instrument. The improvement is due to the higher electrical efficiency of the lasers, the higher detector sensitivity, and the sharper echo pulses from the narrower laser pulses and the smaller laser spots. This efficiency improvement allows the number of spots measured per second to be increased significantly beyond GLAS.

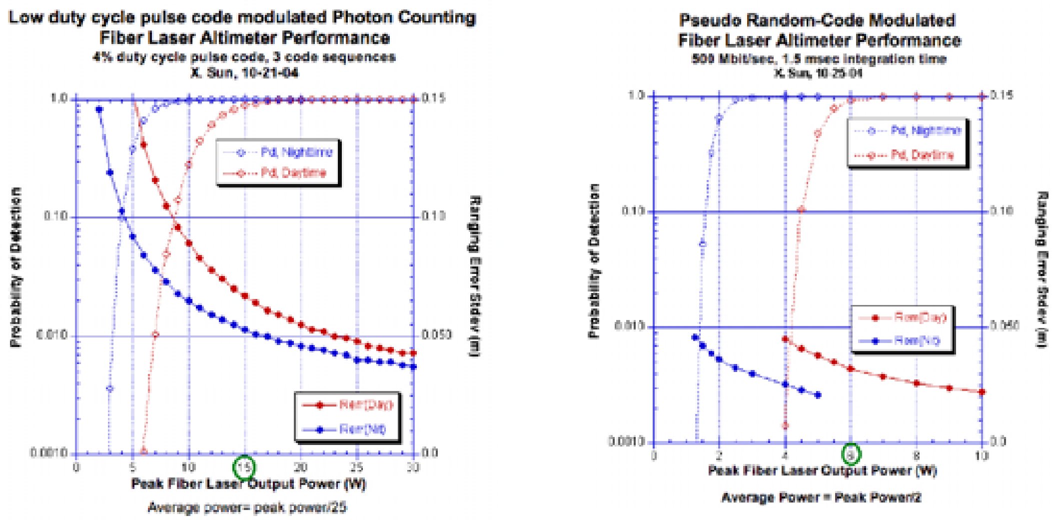

Figure 12. An example of results in the laser measurement tradeoff study for one track of push-broom swath for ice-sheet mapping. Left—Micropulse technique at 4% duty cycle. Right—PN-Code modulation at 500 MHz . The needed average laser powers are 0.6W for this micropulse modulation format and 3 W for the PN-Code modulation.

Publications and Conference Presentations:

We have presented our initial results in three papers at the conferences listed below.

J. B. Abshire, D. Harding, C. Shuman, X. Sun, P. Dabney, M. A. Krainak, and T. Scambos, "Space-based swath imaging laser altimeter for cryospheric topographic and surface property mapping," *Spring AGU 2005,* Paper C43B-04, May 2005.

J. B. Abshire, X. Sun, and M. A. Krainak, "Laser altimetry using pseudo-noise code modulated fiber lasers and photon counting detectors," *Conference on Lasers and Electro-Optics (CLEO'05)*, Paper JThI4, Optical Society of America, May 2005.

J. B. Abshire, D. Harding, X. Sun, M. A. Krainak, C. Shuman, and P. Dabney, "Space-based swath-imaging laser altimeter for cryospheric and topographic mapping," *Fall AGU 2005*, San Francisco, CA, Paper G21C-1288, December 2005.

Planned Future Work:

We proposed this technique in our proposal to the NASA Earth Science Technology Office Instrument Incubator program* and it was selected for funding. The work involves addressing measurement needs for cryospheric science program, as well as examining their benefit to other areas of Earth science.

* D. Harding, J. B. Abshire, X. Sun, C. Shuman, T. Scambos, and P. Dabney, "Push-broom Laser Altimeter Demonstration for Space-based Cryospheric Topographic and Surface Property Mapping," funded under NASA 2005 Earth Science Instrument Incubator Program.

Key Points Summary:

Project's innovative feature: There is considerable scientific benefit from swath-mapping, laser-altimetry measurements from space. However, mapping-altimetry measurements from space are very demanding compared with the currently used laser-profiling approach, which samples along a measurement track. We are developing a new measurement technique to use modulated, long-lifetime fiber lasers coupled with photon-counting detectors to enable high-resolution swath-mapping altimetry from space. The technique is flexible in its configuration.

Potential payoff to Goddard and NASA: There is considerable scientific interest in future space-based mapping-altimeter missions. The Geoscience Laser Altimeter System (GLAS) - the instrument on ICESat - has demonstrated the high-vertical and spatial resolution and compelling value of profiling laser measurements from space. There are needs to measure the heights of icesheets, glaciers, vegetation, and river heights in a future mapping laser-altimeter mission.

Another advantage for this technique is that it allows NASA the opportunity to "leverage" more highly developed technology into space laser altimeters. The fiber lasers we use benefited from the substantial industrial investment in key components and reliability. The photon-counting detectors are available commercially. Ongoing NASA programs are working to further improve detector sensitivity and lifetime. In the future, this approach can be further extended to even smaller laser spots and wider swaths.

Technical risk factors: This approach has risks because the measurement approach is new and it has not been proposed before. Our DDF work has demonstrated the key measurements and addressed their energy scaling to space. As a result, our research has greatly reduced those risks.

Criteria for success: Our criteria for success include showing that the technique makes the needed measurements and that the approach is practical for space use. We have demonstrated those criteria and found our approach to be more flexible than anticipated. We proposed this technique for an ice sheet-mapping altimeter for the recent NASA Earth System Technology Office (ESTO) IIP Research Announcement. It was selected for continued development.