WIDE-SWATH IMAGING LIDAR DEVELOPMENT FOR AIRBORNE AND SPACEBORNE APPLICATIONS

J. Bryan Blair
Laser Remote Sensing Branch
NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
(bryan@arthur.gsfc.nasa.gov)

Michelle Hofton
Department of Geography
University of Maryland, College Park, MD 20742

Scott B. Luthcke
Space Geodesy Branch
NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

KEY WORDS: laser altimetry, lidar, altimetry, mapping.

ABSTRACT

With laser altimetry becoming increasingly accepted by the global Earth science community as a source for accurate topographic data, there is now a desire to apply this technology to large area mapping. Commonly, airborne laser systems provide data at several meter resolution and across swaths up to 1-2 km in width. Economic factors drive commercial systems to widen swaths further, but off-nadir incident angles degrade accuracy and significantly diminish the ability to penetrate dense vegetation canopies effectively limiting swath width. Higher operational altitudes (e.g., 10 km vs. 1 km) can provide up to a factor of ten increase in swath width within a selected angular range. However, higher altitude operations require significantly more laser output power, smaller divergence angles and higher beam quality to achieve smaller footprints. At NASA Goddard Space Flight Center, we have been prototyping spaceborne instrumentation and science applications of wide-swath lidar in aircraft for the last several years. This experience has led to the development of several satellite laser altimeters such as the Shuttle Laser Altimeter (SLA) and Vegetation Canopy Lidar (VCL). Technologies and methods utilized in the spaceborne environment are prototyped in the wide-swath, full-waveform airborne Laser Vegetation Imaging Sensor (LVIS). This sensor will undertake a large-area mapping mission in Brazil in June-August 2002. The sensor will use a 3 km-wide data swath and plans are underway to increase the swath width further. Spaceborne imaging applications require significantly higher effective rep-rates than airborne systems and are much less tolerant of unreliable mechanical scanning and equipment maintenance requirements. Unique scanning and ranging techniques for medium-large footprint, full-waveform mapping laser altimeters are currently under development to enable a spaceborne, wide-swath operational mapping laser altimeter capable of full-Earth mapping and dense vegetation penetration. A sample of some of the techniques being developed at NASA Goddard Space Flight Center for future airborne and spaceborne imaging lidar will be presented, including methods for achieving MHz scanning rates.

1. BACKGROUND

Lidar remote sensing of the Earth's surface for topography and vegetation mapping is becoming increasingly prevalent in airborne and spaceborne activities. Advanced lidar systems record the waveform of the returning laser pulse to provide a record of the interaction of the light pulse with the ground surfaces. Each waveform includes returns from the highest elements of any vegetation and the underlying ground (e.g., Blair et al., 1994). The full illumination (waveform) lidar technique is capable of making high resolution, high accuracy, independent topographic measurements on land, beneath vegetation, and over oceans (e.g., Hofton et al., 2001a). Spaceborne lidar systems such as the Shuttle Laser Altimeter (SLA) (Garvin et al., 1998) have demonstrated sub-meter absolute vertical accuracies for Earth topographic measurements (Luthcke et al., 2001). NASA's future dedicated Earth observing lidar missions, the Vegetation Canopy Lidar (VCL) (Dubayah et al., 1997) and ICESat, will provide unequaled decimeter level vertical absolute accuracies of "true ground" even in highly vegetated regions. NASA's airborne LVIS instrument (Blair et al., 1999), with its wide swath, cm ranging accuracy and the full waveform recording, has provided a wealth of engineering data to prototype space-based lidars and to develop and test data processing algorithms and analysis methodologies.

While the advantages of spaceborne laser active remote sensing are apparent, the major limitation remains data coverage. Both current (SLA) and future (VCL and ICESat) spaceborne lidar missions employ profiling instruments that only illuminate a small portion of the planetary surface (1-2%). Current expectations are that microwave mapping of the Earth's surface from synthetic aperture radar (SAR) interferometry (InSAR) presents the *only* practical method of fully illuminating and characterizing the 3D surface of the planet. While the InSAR measurement technology does provide for full global illumination, the backscattering within canopies, de-correlation of the phase images (caused by vegetation/land cover changes, surface slope, surface freezing/thawing, and random movement of scatterers whose sizes are on the scale of the wavelength of the SAR system), as well as the need for sub-pixel (meter-level) alignment of images limits the overall absolute accuracy of the observations and means accurate topographic and topographic change measurements are impossible in some areas of the Earth. Lidar mapping has distinct advantages in accuracy, resolution, and vegetation penetration. However, there is a clear need to expand these distinct advantages of a lidar system to a spaceborne landscape scale imaging instrument capable of providing full global coverage and monitoring of surface change.

2. AIRBORNE WIDE-SWATH LIDAR

LVIS is a wide-swath, high-altitude, full-waveform airborne laser altimeter developed at NASA Goddard Space Flight Center. LVIS employs mechanical scanning using galvanometer motors to separately scan both the transmitted laser beam and the receiver field-of-view (FOV). LVIS scans in a raster pattern with each mirror coming to a full stop for each laser footprint. Using evolving scan techniques and scan patterns, we can support laser rep-rates of up to 5,000 Hz with this system. This approach has the potential for doubling or quadrupling the swath width, but spaceborne operations and order of magnitude swath increases will require a different approach. Our goal is to begin scanning at 100,000 Hz in the next year with a no-moving-parts scanner system. To support these high laser repetition rates, a different approach toward receiver scanning is required. One option is to segment the receiver FOV across the swath to simulate receiver FOV scanning just by switching detectors and combine this with multiple laser transmitters.

Numerous airborne, swath mapping laser altimeters are currently operational using swath widths from 200 – 2,000 m. To become more cost effective, these systems need to collect data faster and over larger areas. Increasing the swath width requires either operations at higher altitude or increasing the angular swath. Both of these options have negative side effects. Wide angular swaths experience increased sensitivity to errors in attitude knowledge at the swath edges and systems with incident angles >10-15° have increased difficulty penetrating closed vegetation canopies. Further, higher altitude operations also increase sensitivity to attitude errors and require significantly higher laser power to achieve the same performance as that at low altitude.

3. SPACEBORNE WIDE-SWATH LIDAR

Spaceborne implementation of a wide-swath imaging lidar will enable the high accuracy landscape-scale surface observations (Table 1) necessary to answer one of NASA's Earth Science Enterprise (ESE) key questions: *How is the Earth's surface being transformed and how can such information be used to predict future changes?* Wide-swath imaging lidar's high accuracy, high resolution measurements of topography and surface change will lead to significant near-term advances in such fields as the quantification of surface morphology (the first step to understanding constructional and erosional processes and rates) and the mitigation of natural hazards caused by, for example, landslides, flooding and earthquakes. Knowledge of crustal deformation aids in developing and understanding earthquake cycle mechanics and other plate boundary processes (at co, post and inter-event stages). Observations lead to the understanding of volcanic processes particularly for detecting pre-eruption signs and monitoring during/after an eruption, monitoring land subsidence related to human activities such as groundwater, petroleum and coal removal, coastal erosion processes, glacial/ice sheet thickness changes and flow, and post-glacial rebound. Systematic observations of these processes will lead to improved models and forecasting, for example, of eruptive and seismic events, and provide rapid response to emergencies and early warning of hazards. Existing and planned global topographic data sets contain errors (e.g., Wolf and Wingham, 1992), are of insufficient accuracy, resolution, and coverage, or do not fully characterize the true "bare earth" topography needed for global achievement of these science goals. Topographic change measurements are limited to areas where InSAR is possible, or restricted by the poor spatial coverage of techniques such as GPS.

One of the most promising and unique capabilities of laser altimetry is the potential for sensing topography beneath closed vegetation. This is one application that seems to benefit from full-waveform collection. Full-waveform laser altimetry is the only proven method for penetrating the densest of forest canopies. The canopy height and vertical structure information obtained from a full-waveform, wide-swath imaging lidar produce ecological measurements such as biomass and carbon density (Drake et al., 2001; Means et al., 1999), which do not appear to saturate as measurements from SAR technologies do (Imhoff, 1995; Kasischke et al., 1997). These data are important to the ESE Ecology/carbon cycle program. Furthermore, very high-resolution geoid measurements of oceans, topographic corrections for gravity reduction, and coastal oceanography (where radars "lose lock") are possible. For the military (and others), the wide-swath spaceborne imaging lidar can provide data at the DTED3 level (10m posting) with accuracies exceeding DTED5 levels (5m absolute) by an order of magnitude.

Wide-swath imaging lidar measurement technology provides the best characteristics of current InSAR and lidar technologies, enabling the complete illumination of the Earth's surface while maintaining high absolute accuracy (elevation measurements that are 2 orders of magnitude more accurate than the latest InSAR SRTM implementation) mapping of vegetation vertical structure and topography, as well as centimeter level change detection (Hofton and Blair, 2001). Table 1 shows an example of the capabilities of a spaceborne implementation of this technology.

Table 1:
A spaceborne implementation of the proposed wide-swath imaging lidar technology will enable:

- Landscape scale (10km swath) imaging
- Full Earth imaging at <10m pixels within 1 year
    - Near-100% coverage/illumination
- Topography measurements at decimeter-level absolute vertical accuracy
- Vegetation canopy height and structure measurements
- Change detection measurements at sub-centimeter relative vertical accuracy
    - Subtle topographic change beneath vegetation,
- Vegetation and land cover changes.

To enable spaceborne imaging lidar requires that we advance the readiness of several key technologies associated with laser scanning and laser range recovery, as well as advance post processing techniques to allow cm-level change detection and improve signal to noise ratio within the lidar footprints. Efforts are currently underway to develop: no-moving-parts scanning systems, large aperture deployable telescopes (Browell, et al., 2001), and high-efficiency laser transmitters.

4. SUMMARY

At NASA Goddard Space Flight Center, ongoing development of wide-swath airborne laser altimeters support future development of a spaceborne imaging lidar system for fully mapping the Earth's surface topography (including sub-canopy) and vegetation vertical structure. Several techniques for achieving wide data swaths from a spaceborne laser altimeter are under investigation. An airborne demonstration of 100 kHz, no-moving-parts, high-rate laser scanning coupled with a segmented FOV receiver is planned for the near future. Ultimately, an operational spaceborne swath imaging laser altimeter system will require sampling rates of 1 MHz or greater.

5. REFERENCES

Blair, J.B., Coyle, D.B., Bufton, J.L., and Harding, D.J., 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. In: Proceedings of the International Geoscience and Remote Sensing Symposium – IGARSS 1994. ESA Scientific and Technical Publications, Noordwijk, pp. 939-941.

Blair, J.B., Rabine, D.L., and Hofton, M.A., The Laser Vegetation Imaging Sensor: a medium-altitude digitization-only, airborne laser altimeter for mapping vegetation and topography, ISPRS Journal of Photogrammetry and Remote Sensing, 54, 115-122, 1999.

Browell, E., Peri, F., and Connerton, R., Light-weight deployable UV/Visible/IR telescopes, presented at ESE Technology Planning workshop, 2001.

Dubayah, R., Blair, J.B., Bufton, J.L., Clark, D.B., Ja Ja, J., Knox, R., Luthcke, S.B., Prince, S., and Weishampel, J., The Vegetation Canopy Lidar mission. In: Land Satellite Information in the Next Decade II: Sources and Applications, American Society for Photogrammetry and Remote Sensing, Bethesda MD, pp. 100-112, 1997.

Drake, J., Dubayah. R., Clark, D., Knox, R., Blair, J.B., Hofton, M.A., Chazdon, R.L., Weishampel, J. F., and Prince, S., Estimation of tropical forest structural characteristics using large-footprint lidar, in press, Remote Sensing of Environment, 2001.

Garvin, J. B., Bufton, J., Blair, J., Harding, D., Luthcke, S., Frawley, J., and Rowlands, D., Observations of the Earth's topography from the Shuttle Laser Altimeter (SLA): Laser pulse echo-recovery measurements of terrestrial surfaces, Physics and Chemistry of the Earth, 23, 1053-1068, 1998.

Hofton, M. A., Blair, J. B., Minster, J.-B., Ridgway, J. R., Williams, N.P., Bufton, J.L., and Rabine, D.L., An airborne scanning laser altimetry survey of Long Valley, CA, International Journal of Remote Sensing, 21, 2413-2437, 2000a.

Hofton, M.A., and Blair, J.B., Detecting vertical ground surface change using laser pulse correlation, submitted to Journal of Geodynamics, 2001.

Imhoff, M.L., 1995. Radar backscatter and biomass saturation-ramifications for global biomass inventory. IEEE Transactions on Geoscience and Remote Sensing, 33, 511-518.

Kasischke, E.S., Melack, J.M., and Dobson, M.C., 1997. The use of imaging radars for ecological applications – a review. Remote Sensing of the Environment, 59, 141-156.

Luthcke, S.B., Rowlands, D.D., McCarthy, J.J., Stoneking, E. and Pavlis, D.E., Spaceborne Laser Altimeter Pointing Bias Calibration From Range Residual Analysis, Journal of Spacecraft and Rockets, 37, 2000.

Means, J.E., Acker, S.E., Harding, D.J., Blair, J.B., Lefsky, M.A., Cohen, W.B., Harmon, M.E., and McKee, W.A., use of large footprint scanning airborne lidar to estimate forest stand characteristics in the western Cascades of Oregon, Remote Sensing of the Environment, 67, 298-308, 1999.

Wolf, M., and Wingham, D.J., The status of the world's public-domain digital topography of the land and ice, Geophysical Research Letters, 19, 2325-2328, 1992.