CONNECTING THE DOTS BETWEEN WAVEFORM LIDAR, WOODY AND HERBACEOUS BIOMASS, AND FRACTIONAL COVER FOR ASSESSMENT OF LAND DEGRADATION USING SMALL-FOOTPRINT WAVEFORM LIDAR DATA

J. Wu[1], J.A.N. van Aardt[1], G.P. Asner[2], R. Mathieu[3], T. Kennedy-Bowdoin[2], D. Knapp[2], K. Wessels[3], B. Erasmus[4], I. Smit[5]

[1]Rochester Institute of Technology, Rochester, 14623, NY, USA
[2]Carnegie Institution for Science, Stanford, 94305, CA, USA
[3]Council for Scientific and Industrial Research, 0001, Pretoria, South Africa
[4]University of the Witwatersrand, 2001, Johannesburg, South Africa
[5]Kruger National Park Scientific Services, 1350, Skukuza, South Africa

1. INTRODUCTION

Land degradation, defined as a persistent reduction in the capacity of the ecosystem to deliver ecosystem services such as grazing, fuelwood or habitat for wildlife, is regarded as one of the most important environmental issues facing Sub-Saharan Africa. In South Africa it is especially prevalent in the communal lands of the former segregated "homelands". Land degradation assessment has been a topic of intense research, e.g., [1], but is approaching a point at which regional modelling and monitoring are limited by the capabilities of traditional remote sensing technology. One of the limiting factors is the reliance on high frequency, low spatial resolution, multi-spectral (3-20 wavebands) remote sensing data (e.g. 1km/pixel AVHRR or 500m/pixel MODIS), which are intended to develop regional indicators of vegetation production. This spectrally-and spatially coarse resolution data cannot unravel changes in the land surface at the scale at which the processes actually occur (a few meters). Nor can they identify vegetation composition, structure, and function. It has become evident that improved monitoring of land degradation requires measurements of the ecosystem with (i) a broader wavelength range, defined in narrower wavelength bins (imaging spectroscopy) [2] and (ii) sensors capable of describing the 3-dimensional vegetation structure, e.g. light detection and ranging (lidar). Lidar has been applied extensively in forested environments to describe structural parameters (e.g., volume and biomass; [3, 4]). However, waveform lidar, which records and digitizes the full-backscattered signal with high resolution (~1ns), is a relatively recent technology that holds much promise for detailed vertical characterization of vegetation structure (e.g., [3, 5]). The Carnegie Airborne Observatory (CAO; http://cao.stanford.edu) is a truly unique remote sensing platform in that it combines both the hyperspectral and waveform lidar technologies described above to study regional ecosystems anywhere in the world.

The CAO mission is to "understand how land-use change, climate change and natural disturbances are affecting the structure and function of ecosystems, and how these changes alter the services provided by ecosystems to people" (http://cao.stanford.edu). The CAO can be operated in two modes, depending on research/user needs. The CAO "*Alpha*" mode is the core configuration, consisting of an imaging spectrometer (hyperspectral sensor) and a small-footprint scanning-waveform lidar system on an integrated platform. The imaging spectrometer can acquire imagery in up to 288 channels of 1.8-nm bandwidth (FWHM) in the 400-1050 nm wavelength range and has a swath of 1,500 pixels. The spectrometer is co-mounted with the scanning lidar (100 kHz) with full waveform digitization. The lidar collects both discrete- and waveforms returns on separate systems. CAO algorithms ensure that data inputs from the spectrometer and the lidar system is automatically co-located to ensure geographically aligned output. These instrument configurations are able to provide high spatial resolution 3D information on the structure, biochemistry and physiology of ecosystems [6]. The CAO constitutes the ideal sensor for research towards an improved understanding of land degradation dynamics at fine scales.

The juxtaposition of the Kruger National Park (KNP) to private game reserves and degraded areas in the Lowveld, South Africa, furthermore allows us to investigate the added value of especially waveform lidar for quantifying the impacts of degradation on vegetation structure. The objectives of this research thus were to (i) assess the ability of waveform lidar data to quantify woody and herbaceous biomass and (ii) establish the relationship between fractional cover, derived from concurrent studies, and waveform lidar metrics.

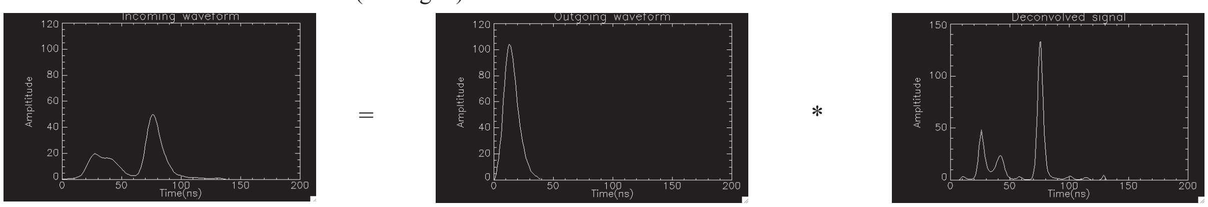
2. METHODS

The study area is located in the Kruger National Park and surrounds, in the Mpumalanga Province of South Africa, and is bounded by (22°8'00" S; 30°34'52"E) and (25°32'48"S; 32°2'50"E). Structural assessment of land degradation across a land use gradient (KNP-homelands) will be performed using waveform lidar (0.56 m), acquired during April, 2008. Field data consist of individual tree measurements (height, crown height, diameter, and species), site- (50 m x 50 m), and plot-level (36 plots/site; ± 5 m radius plots) measurements. Sites were located across geological substrata (basalt and granite) and landscape positions (crest, mid-slope, and footslope). Plot-level data consist of herbaceous biomass samples, within-plot tree height and diameter measurements, and qualitative assessment of cover (crusting, bare soil, herbaceous, and woody cover). These measurements will be scaled to site-level for landscape analysis. Our analysis will start at the individual tree level, with per-pixel waveform data aggregated across the plot and site levels as biomass-waveform relationships are developed. Additionally, the impact of fractional cover (photosynthetic, non-photosynthetic, and bare soil) on waveform response will be evaluated. Fractional cover will be provided by concurrent studies that utilize imaging spectroscopy data. We will attempt to extract structural metrics from the waveforms in order to explain variation in woody and herbaceous biomass field measurements and fractional cover estimates from imaging spectroscopy. However, a precursory step involves proper waveform lidar pre-processing, most notably deconvolution of the outgoing waveform pulse from the return (incoming) waveform registered by the sensor. This is required to normalize for outgoing pulse variations, as well as for the changes in the detector response function [7]:

$$P_r(t) = P_t(t) * \sigma(t) * \Gamma(t) \qquad [1]$$

where $P_r(t)$: incoming waveform (*known*)
$P_t(t)$: outgoing waveform (*known*)
$\sigma(t)$: backscatter cross-section of the target (*needs to be solved*)
$\Gamma(t)$: receiver impulse response (*estimated/measured*)

The final incoming (received) waveform typically exhibits a stretched and featureless character, mainly due to a fixed time resolution and the sensor's unstable outgoing pulse signal and receiver impulse response. The purpose of deconvolution is to recover the true response distribution of optically active substances along the path of the lidar waveform. Recovery of the true response distribution, defined by the backscattered cross-section, $\sigma(t)$, which characterizes target size, reflectivity, and the directionality of the scattering, also increases the effective distance resolution of detector (see Fig. 1)



(Received waveform) (Outgoing waveform) (Deconvolved waveform)

Fig.1 Illustration of waveform deconvolution (Richardson-Lucy algorithm [8, 9] and assuming a delta function for the receiver response)

Gaussian decomposition [7], which models the waveform as a sum of Gaussian functions, can be employed following the waveform deconvolution to further extract waveform structural metrics, e.g., peak position, width, etc.

3. CONCLUSION

We hypothesize that the incoming waveform will be a function of both woody and herbaceous biomass and that biomass can be characterized through waveform metrics, e.g., integrals, mode, etc. We furthermore expect that herbaceous biomass and fractional cover will be closely related to especially the ground-specific waveform component, i.e., the last mode in a multi-modal waveform, through potential "spread" of the signal as a function of vegetation cover. The research is continuing and results will be presented at the conference.

4. REFERENCES

[1] K.J. Wessels, S.D. Prince, M. Carroll, and J. Malherbe, "Relevance of rangeland degradation in semiarid northeastern South Africa to the nonequilibrium theory", Ecol. Appl., vol. 17, pp. 815-827, 2007.
[2] G.P. Asner, C.E. Borghi, and R.A. Ojeda, "Desertification in central Argentina: Changes in ecosystem carbon and nitrogen from imaging spectroscopy", Ecol. Appl., vol. 13, no. 3, pp. 629-648, 2003.
[3] M.A. Lefsky, D. Harding, W.B. Cohen, G. Parker, and H.H. Shugart, "Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA", Remote Sens. Environ., vol. 67, pp. 83-98, 1999.
[4] J.A.N. van Aardt, R.H. Wynne, and R.G. Oderwald, "Forest Volume and Biomass Estimation Using Small-Footprint Lidar-Distributional Parameters on a Per-Segment Basis", Forest Sci., vol. 52, no. 6, 636-649, 2006.
[5] J.B. Blair, J.B., and M.A. Hofton, "Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data", Geophys. Res. Lett., vol. 26, no. 16, pp. 2509-2512, 1999.
[6] G.P. Asner, D.E. Knapp, M.O. Jones, T. Kennedy-Bowdoin, R.E. Martin, J. Boardman, and C.B. Field, "Carnegie Airborne Observatory: In-flight fusion of hyperspectral imaging and waveform light detection and ranging (wLiDAR) for three-dimensional studies of ecosystems", J. Appl. Remote Sens., 1, DOI: 10.1117/1.2794018, 2007.
[7] W. Wagner, A. Ullrich, V. Ducic, T. Melzer, N. Studnicka, " Gaussian decomposition and calibration of a novel small-footprint full-waveform digitizing airborne laser scanner", ISPRS J. Photogramm., vol.60, pp.100-112, 2006.
[8] Richardson, William Hadley (1972). "Bayesian-Based Iterative Method of Image Restoration". JOSA., vol. 62, no.1, pp. 55–59, 1972.
[9] Lucy, L. B, "An iterative technique for the rectification of observed distributions". Astron. J., vol. 79 , no.6, pp. 745–754, 1974.