Ecological Informatics 38 (2017) 82–88

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

Estimating signal loss in pine forests using hemispherical sky oriented photos

William C. Wright *, Benjamin E. Wilkinson, Wendell P. Cropper Jr

Department of Forestry, University of Florida, Gainesville, FL, USA

ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 3 February 2017
Accepted 7 February 2017
Available online 10 February 2017

Keywords:
Canopy closure
Global positioning system
Hemispherical sky oriented photo
Leaf area index
Signal attenuation
Geographic information system

ABSTRACT

We depend on numerous technologies that use microwave signals. The reception of these signals is degraded by reflection, absorption, and scattering due to propagation through vegetation. An understanding of how these signals are influenced by vegetation structure allows for the determination of how specific technologies may be affected in certain forest environments. This study presents a model that predicts signal loss in forested areas using novel methods. We explore the relationships between forest parameters from traditional mensuration techniques and terrestrial-based hemispherical sky oriented photos (HSOPs), and GPS signal-to-noise ratios (SNRs). HSOPs can be used to rapidly estimate leaf area index (LAI) and canopy closure (CC) values at particular angles from zenith in forested areas. The relationships between changes in the observed SNR of received GPS L1-band signals under forest canopies and forest parameter estimates calculated using HSOPs and traditional forest measurements are used to model signal attenuation. Using ordinary least squares regression modeling, we present the *Canopy Closure Predictive Model* (CCPM). The CCPM outlines the key forest parameters used with an adjusted R^2 of 0.71 and RMSE of 2.78 dB. The resulting CCPM predicts signal attenuation while using only the minimum number of statistically-significant parameters which, conveniently, are taken from sky oriented photos and GPS receivers allowing for simple and rapid replication.

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1. Introduction

Civilian and military organizations rely heavily on the technologies that utilize microwave transmissions. Jungle and forest structure are known to attenuate these microwave signals. This research presents a method to predict how the forest conditions in a managed pine forest attenuated these signals. While this research uses signal observations from GPS satellite vehicles (SVs), the model presented provides an insight into how other technologies will also be influenced.

There is significant interest in researching forest characteristics due to the multitude of different processes affected by forest canopy. Many studies have focused on how sunlight, radio waves, and lidar propagate through forest canopy. Research focused on canopy conditions includes studies ranging from carbon stock estimates (Stark et al., 2012), forest management and inventory methods (Gong et al., 1999; Jasinski, 1996; Leckie, 1990; Leckie et al., 1998; Moskal and Zheng, 2011; Uusitalo, 1997; Uuttera et al., 1998), classification methods (Key et al., 2001; Puttonen et al., 2011; Sayn-Wittgenstein, 1978), and habitat studies (Holopainen and Wang, 1998). Similarly, studies have investigated the relationship between light interception and forest structure (Bode et al., 2014; Gonzalez-Benecke et al., 2014; Mücke and Hollaus, 2011), forest fuel estimation (Andersen et al., 2005), biomass estimates (Bortolot and Wynne, 2005; Drake et al., 2002), and growth dynamics (Hosoi and Omasa, 2009). Research utilizing GPS signals have explored wireless communication effectiveness, GPS position accuracy, and timber volume estimation (Andrade, 2001; Lee et al., 2005; Lee et al., 2009; Lee et al., 2010; Wright et al., 2008; Wright et al., 2017). Recently, some work has also focused on how microwave attenuation through vegetation relates to water content and crop health (Wan et al., 2014; Luo et al., 2014).

There has been a military interest in GPS performance in forests and the impact of specific forest parameters on GPS performance (Holden et al., 2001). Communication and military target acquisition in forest and jungle environments are of particular interest (Massaro et al., 2012; Mätzler, 1994; Swanson et al., 2009; Ulaby et al., 1990; Weissberger, 1982; Wright et al., 2008). The US military plans for operations in regions all over the world. In many instances these plans are prepared before any projected conflicts arise so that a base plan is available in the event an operation must be conducted at a moment's notice. These plans include combat operations, humanitarian assistance, and

Abbreviations: HSOP, Hemispherical sky oriented photo; SNR, Signal-to-noise ratio; LAI, Leaf area index; CCPM, Canopy closure predictive model; IMPAC, Intensive Management Practice Assessment Center; DBH, Diameter at breast height; GLA, Gap light analyzer; CC, Canopy closure; SV, Satellite vehicle; NMEA, National Marine Electronic Association; CNR, Carrier-to-noise ratio.

* Corresponding author at: 406A Reed Lab, P.O Box 110565, University of Florida, Gainesville, FL 32611-0565, United States.

E-mail address: X97068@ufl.edu (W.C. Wright).

http://dx.doi.org/10.1016/j.ecoinf.2017.02.002
1574-9541/Published by Elsevier B.V.

peacekeeping operations. Many of these contingency plans call for operations in savanna or dense forest environments. The canopy associated with forest and jungle environments are known to scatter and reflect signals that many of the operational technologies are dependent upon. Technologies such as AM/FM radio, satellite communication, GPS, lidar, and radar are just a few that could be adversely affected by canopy. An understanding of how specific technologies that rely on microwave transmission and reception are impacted by forest canopy could provide planners with the ability to properly identify the right technologies to use in differing forest and jungle conditions.

When considering modeling signal loss in a forest environment, it is important to consider different existing vegetative models. The Beer-Lambert's law, often just referred to as Beer's law, is the most straightforward approach and most logical place to start when discussing models of forest canopy transmittance. Beer's law was originally used to describe light extinction as it passes through water with a determined amount of uniformly distributed particulate. The original formula is:

$$I_n = I_O * e\left(1 - \frac{k*P}{N}\right) \tag{1}$$

Where I_n is the intensity of light at depth n, I_O is the intensity of the light before entering the column, P is the projected surface area of the particulate, and k is the extinction coefficient. Beer's law adapts easily to the modeling of light distribution through forest canopies and is the basis for many of the more complex models (Larsen and Kershaw, 1996; Ross, 1981). When considering a uniformly distributed forest canopy, Beer's law suggests the absorption of light exhibits a linear dependence between the path length of the light through the medium, the absorption coefficient, and the concentration of medium. This yields the equation:

$$L = \alpha dc \tag{2}$$

where, L is attenuation, d is the path length in the medium, c is the concentration of the absorbing material, and α is the absorption coefficient (Wright et al., 2008). In these cases the media in which the signal passes through is forest foliage, but the precise absorption coefficients of the foliage are not assumed. As a result, the factors α and c are combined into a single parameter B, yielding the simplified equation (Liu et al., 2011):

$$L = Bd \tag{3}$$

When applying a model to studies focusing on signal loss through forests using GPS receivers, attenuation is calculated using the Carrier to Noise Ratio (CNR) of a given satellite. Often CNR is used interchangeably with SNR, for simplicity, we will use SNR henceforth. SNR readings must be observed in both an open area, as well as, under the vegetation and then compared to one another. These observations are measured in decibels making the calculation of L very simple compared to the methods outlined by Rodriguez (Rodriguez-Alvarez et al., 2012). While obtaining the power of a GPS signal is not easily obtained in normal GPS messages, the SNR values are reported using the National Maritime Electronic Association (NMEA) messaging in the "GPGSV" message string reported in decibels. These reported SNR observations are therefore expressed in the following manner:

$$SNR = 10\,log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \tag{4}$$

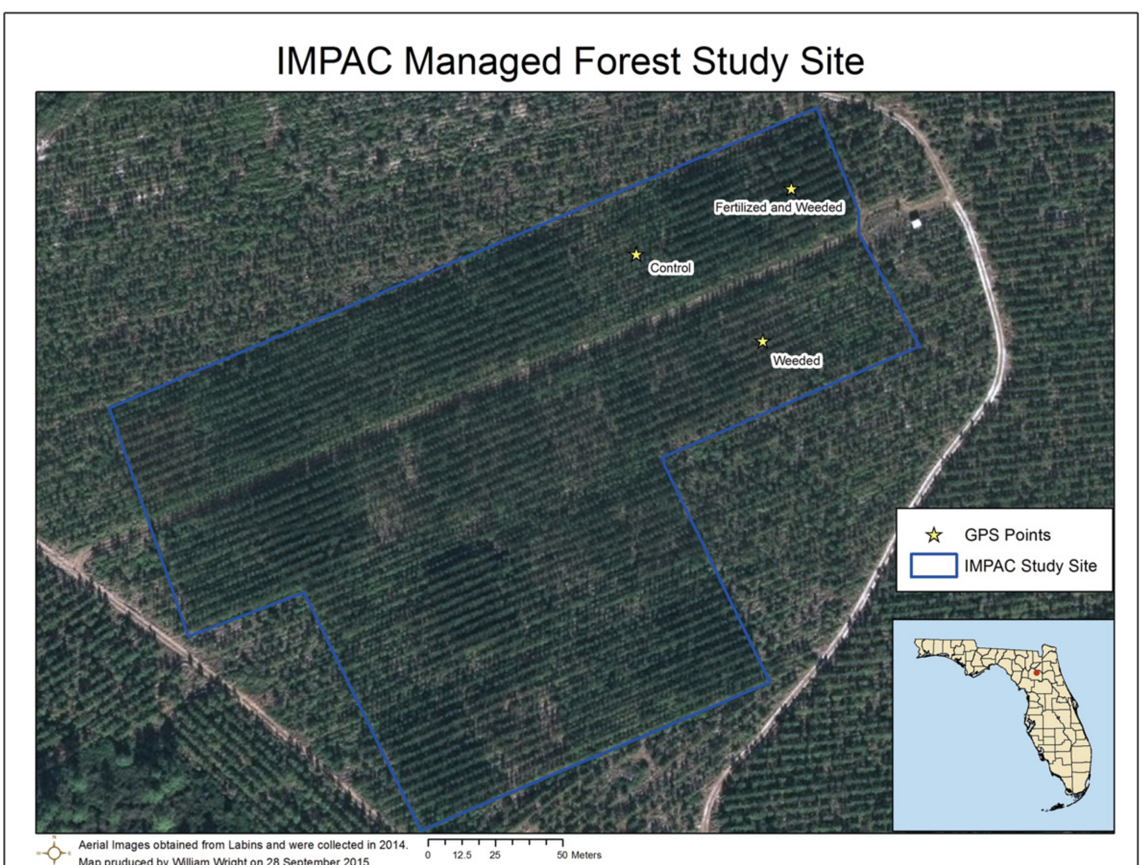

Fig. 1. A map of the IMPAC forest study site and the location of the GPS setup sites (2014).