THE AMBIGUITY IN FOREST PROFILES AND EXTINCTION ESTIMATED FROM MULTIBASELINE INTERFEROMETRIC SAR

A ambigüidade em perfis da floresta e extinção estimada por interferometria SAR através de múltiplas linhas de base

ROBERT N. TREUHAFT [1]
BRUCE D. CHAPMAN [1]
JOÃO ROBERTO DOS SANTOS [2]
FABIO G. GONÇALVES [3]
LUCIANO V. DUTRA [2]
PAULO MAURÍCIO L. A. GRAÇA [4]
JASON B. DRAKE [5]

[1] Jet Propulsion Laboratory, California Institute of Technology
Pasadena, 91109 CA, USA
email: robert.treuhaft@jpl.nasa.gov
[2] Instituto Nacional de Pesquisas Espaciais
Av. dos Astronautas, 1758
CEP-12.227-010 - São José dos Campos, SP, Brasil
email:jroberto@dsr.inpe.br
[3] Oregon State University
Corvallis, 97331 – OR, USA
email: fabio.goncalves@oregonstate.edu
[4] Instituto Nacional de Pesquisas da Amazônia,
Av. André Araujo, 2936
CEP - 69060-001 - Manaus, AM, Brasil
email: pmlag@inpa.gov.br
[5] USDA Forest Service
Tallahassee, 32303 – FL, USA
email: jasondrake@fs.fed.us

ABSTRACT

This paper demonstrates by simulation that in the estimation of vegetation profiles from multibaseline interferometric synthetic aperture radar (InSAR), the peak extinction coefficient is poorly determined for typical interferometric coherence and phase accuracies. This coefficient determines overall density and affects the relative density profiles estimated from interferometry. This paper shows that a given radar power profile gives rise to a family of vegetation density profiles, depending on the peak extinction assumed. It is further demonstrated that estimating the peak extinction requires coherence accuracies of better than 0.1% and phase accuracies of better than a few tenths of a degree, both of which exceed the performance of typical or envisioned SAR systems. Two recommended approaches to profile production with InSAR are 1) use the radar power profile instead of the vegetation density profile for biomass estimation and other ecosystem characterization (in analogy to LIDAR power which is most frequently used for lidar studies of biomass) or 2) apply external information to establish the extinction characteristics needed for vegetation density profiles.

Keywords: Interferometry; Forest; Extinction Coefficient; SAR; InSAR; Remote Sensing.

RESUMO

Esse artigo procura demonstrar, por simulação, que na estimativa de perfis de volume da vegetação por interferometria com múltiplas linhas de base, o pico de extinção não é adequadamente determinado pela coerência interferométrica e fase, com acurácias típicas de InSAR. Esse pico determina a densidade global, afetando os perfis de densidade relativa da vegetação estimados por interferometria. Esse trabalho mostra que para um dado perfil de potência-radar há uma série de perfis de densidade da vegetação, dependendo do pico de extinção assumido. É ainda demonstrado que a estimativa do pico de extinção requer exatidões de coerência melhores que 0,1%, bem como, de acurácias de fases que alguns décimos de graus, valores esses que atualmente excedem o desempenho de sistemas SAR em operação ou aqueles previstos. As duas abordagens recomendadas para a produção de perfis com InSAR são: (1) utilizar o perfil-radar, ao invés do perfil de densidade de vegetação, para estimação de biomassa e outras caracterizações de ecossistema (em analogia à potência-lidar, a qual é mais frequentemente utilizada nos estudos de biomassa baseados em LIDAR); ou (2) aplicar informação externa para estabelecer as características de extinção necessárias aos perfis de densidade de vegetação.

Palavras-chave: Interferometria; Floresta; Coeficiente de Extinção; InSAR; Sensoriamento Remoto.

1. INTRODUCTION

The structural characteristics of forest typologies are used as an indicator of the volumetric and biomass distribution (important in studies of the global carbon cycle), and of the fragmentation level and loss of biodiversity, which is a result from degradation processes within the forest domain. The use of microwave remote sensing, the exploration of scattering mechanisms and synthetic aperture radar attenuation signals at multi-frequencies and polarimetric aspects interacting with different structural vegetation features, are referenced in HENDERSON and LEWIS (1998), HOEKMAN and QUIÑONES (2000), and NARVAES et al (2007). Other authors discuss the contribution of interferometric synthetic aperture radar (InSAR) to study the 3-dimensional forest structure and to estimate biophysical parameters and forest biomass classification (BALTZER, 2001; SANTOS et al., 2003; NEEFF et al., 2005; TREUHAFT et al., 2006).

There is a growing body of evidence that functions or moments of forest vegetation profiles, as opposed to simple heights, will be required of remote sensing, whether microwave or optical, for the most accurate biomass estimation (e.g. DRAKE et al., 2002; TREUHAFT et al., 2003). Biodiversity estimates will probably also require more vertical structure information than some suitably defined vegetation height (e.g. MacARTHUR and MacARTHUR, 1961). While full profiles may frequently not be needed for forest monitoring, it appears that some level of profile information may well be necessary. Profile estimation has been undertaken with multibaseline InSAR to explore the fundamental capabilities of the technique and the accuracies required for subsequent applications (TREUHAFT et al., in press). As a part of the referenced study, in this paper we show by simulation that InSAR is unambiguously sensitive to radar power profiles. However, for each unambiguous power profile is a family of vegetation density profiles, each one corresponding to a different peak extinction coefficient. In turn, it is shown that this peak extinction coefficient cannot be estimated accurately given typical InSAR errors. The difficulty in specifying the correct member of the family of admissible vegetation density profiles prompts the ambiguity in density-profile estimation. It is recommended that either power profiles be used or external information be applied from which extinction can be inferred.

The simulation in this paper is based on a 14 baselines InSAR experiment measuring primary forest, secondary forest, and abandoned-pasture sites at La Selva Biological Station in Costa Rica. This experiment is described completely in TREUHAFT et al. (in press). It was conducted at C-band with the NASA AirSAR radar. The derivative of interferometric phase with respect to height above the ground is the characteristic feature of an InSAR system; it depends on baseline, wavelength, radar altitude, and incidence angle (TREUHAFT et. al. 1996). This derivative ranged from 0.04 to 0.5 rad/m in this simulation. A principal result from the experiment also used in the simulation was the relative density profile, which was estimated from field measurements of height-to-base-of-crown and total height, as well as the lateral extents of tree canopies for one secondary stand. This relative density profile was then normalized with a peak extinction of 0.1 dB/m, which gave the best agreement with field and lidar measurements in the actual data for the 30 stands measured in the experiment. Though not directly applied to the simulation, the plot sizes for InSAR and field data at La Selva were 50 m x 50m and 10 m x 100 m respectively.

2. DENSITY PROFILES, POWER PROFILES, AND PEAK EXTINCTION

For randomly oriented vegetation volumes, the InSAR cross correlation, which is the fundamental InSAR observation, for a vegetation volume, can be expressed as a function of baseline B, wavelength λ, and incidence angle Θ_0, depends on vegetation density as follows:

$$cross\ cor(B,\lambda,\theta_0) \propto e^{i\phi(z_0)} \int_0^{\infty} dz'\ e^{i\alpha_z(B,\lambda,\theta_0)z'}\ \rho(z')\ \left\langle f_b^2(z')\right\rangle \exp\left[\frac{-2}{\cos\vartheta_0}\int_{z'}^{\infty} dz''\ \sigma_x(z'')\right] \quad (1)$$

This integral over the vertical direction *z'*, from TREUHAFT et al. (1996), is normalized by *cross cor*(B = 0,λ,Θ_0) to calculate the complex coherence:

$$complex\ coherence = \frac{e^{i\phi(z_0)} \int_0^{\infty} dz'\ e^{i\alpha_z(B,\lambda,\theta_0)z'}\ \rho(z')\ \left\langle f_b^2(z')\right\rangle \exp\left[\frac{-2}{\cos\vartheta_0}\int_{z'}^{\infty} dz''\ \sigma_x(z'')\right]}{\int_0^{\infty} dz'\ \rho(z')\ \left\langle f_b^2(z')\right\rangle \exp\left[\frac{-2}{\cos\vartheta_0}\int_{z'}^{\infty} dz''\ \sigma_x(z'')\right]} \quad (2)$$

The <> brackets indicate an average over scatterer type—branches, leaves, trunks—signifying an average scatterer strength as a function of height above the ground. In (1), α_z is the derivative of interferometric phase with respect to height above the ground, and $\phi(z_0)$ is the interferometric phase at the ground level. The 2 terms between the exponentials determine the brightness of the vegetation as a function of height, with ρ(z) being the number of scatterers per unit volume at *z* and $\left\langle f_b^2(z)\right\rangle$ the average brightness of a scatterer at *z*. The last exponential accounts for attenuation of the waves propagating forward or backward in the medium. $\sigma_x(z)$ is the extinction coefficient at *z* and is also proportional to ρ(z). It is expressed in db/m, but the actual number used in (1) or (2) is not converted to db/m, but is in the units of m^{-1}, as in (29) of TREUHAFT et al. 1996. It is usually assumed that $\left\langle f_b^2(z)\right\rangle$ is independent of *z* and that ρ(z) is proportional to the vegetation leaf area density (TREUHAFT et al., 2002); ρ(z) will be called the "profile of vegetation density" or "relative density profile", depending on the normalization, from here on. The last three terms of (1) can be combined as f(z), the radar power received from altitude *z*:

$$cross\ \ cor(B,\lambda,\theta_0) \propto e^{i\phi(z_0)} \int_0^{\infty} dz'\ e^{i\alpha_z(B,\lambda,\theta_0)z'}\ \ f(z') \qquad (3)$$

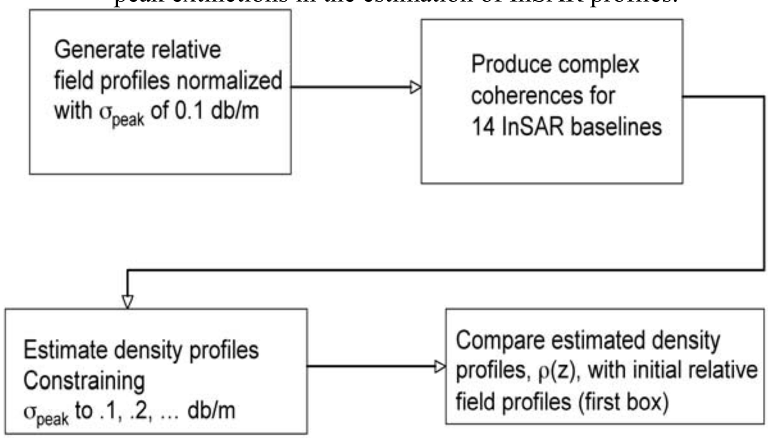
Note that for very low attenuation, under the assumptions already mentioned, the radar power profile is proportional to $\rho(z)$, which in turn is assumed proportional to the vegetation density. But in the presence of attenuation, increasing extinction with a given power profile implies more vegetation at lower altitudes; that is, the radar power will be peaked at higher altitudes than the actual vegetation density.

In order to understand the family of vegetation profiles corresponding to a single radar profile, consider parameterizing $\rho(z)$ in (1) with 12 5-m height bins from 0 to 60 m. With $\left\langle f_b^2 \right\rangle$ assumed independent of altitude and normalizing the peak of $\rho(z)$ to be 1, the relative value of each of these bins will be the relative vegetation profile density. In this parameterization, the extinction is also considered to vary with $\rho(z)$ as

$$\sigma_X(z) = \sigma_{peak}\ \ \rho(z) \qquad (4)$$

By simulating a relative vegetation density and a normalizing extinction and then estimating the 12 parameters with different constrained values of σ_{peak} in the analysis, we can determine the degree to which multibaseline InSAR is capable of estimating both a relative profile and peak extinction. Figure 1 shows the program for determining the degree to which peak extinctions can be estimated from 14-baseline InSAR data.

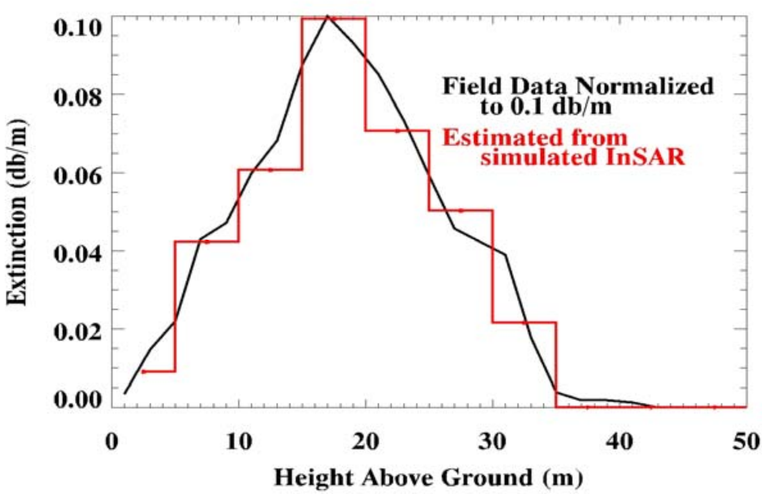
Figure 1 - Flow chart for simulation evaluating the effect of assuming different peak extinctions in the estimation of InSAR profiles.



Initially, field measurements from La Selva Biological Station in Costa Rica from a secondary stand were converted to relative density profiles $\rho(z)$ and normalized by a "truth" σ_{peak} of 0.1 dB/m. Complex InSAR coherences as in (2) were produced for 14 baselines with α_z from 0.04 rad/m to 0.5 rad/m, all at Θ_0 of 35°, simulating the real InSAR data in Costa Rica (TREUHAFT et al., in press). Those 14 complex coherences were then used as data, with an assumed peak extinction the same as the "truth" extinction, and profiles of vegetation density $\rho(z)$ were estimated.

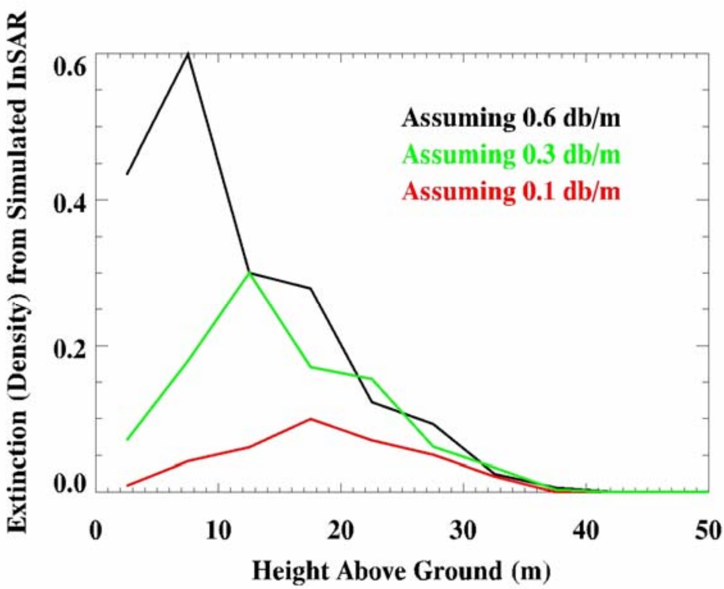
Figure 2 shows that when the true value of peak extinction is assumed, the InSAR-estimated profile in red agrees well with the field profile in black—the only thing really being tested here is whether the 12-level parameterization is sufficient to estimate the original profile. Figure 2 shows the field profile normalized to 0.1 dB/m in black and the 12-level estimate of the profile in red from the simulated InSAR data. Figure 2 demonstrates that the parameterization and estimation process recovers the original profile well with the 14 baselines used, if the correct "truth" peak extinction is used—though for real data this peak extinction is not known. As suggested in Figure 1, this process was then repeated, with assumed peak extinctions in the estimation process different from the "truth" extinction.

Figure 2 - Field profile (black curve) calculated from tree dimensions on a 10 x 100 m transect, assuming the peak extinction of 0.1 dB/m. The red curve is the profile estimated from the 14 baselines simulated data generated from the black curve, using the correct "truth" extinction as a constraint.

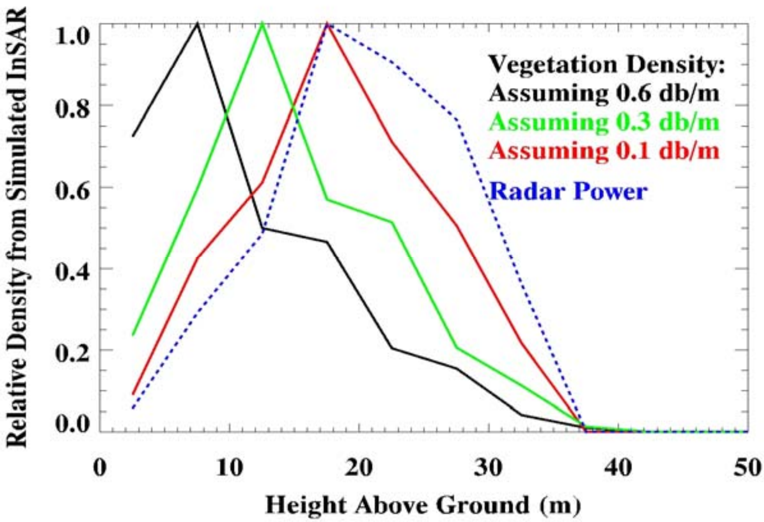


The estimated profile of Figure 2 is in Figure 3 in red, shown for clarity as a continuous curve rather than a step function. Also shown are the results of repeating the estimation of the same "truth" data with peak extinctions constrained to be deliberately away from the "truth" value at 0.3 dB/m and 0.6 dB/m. Figure 3a shows, as expected, that as the extinction is increased, the vegetation density peak moves to lower heights. Figure 3b shows the same thing, with all curves normalized to a peak relative density of 1.0. If, as will be shown, the InSAR data alone cannot uniquely estimate the peak extinction very well, the family of vegetation density profiles including the black, red, and green curves would all be allowed by the data; hence the ambiguity in density profile estimation. Also shown in Figure 3b is the unambiguous unity-normalized radar power profile, which is consistent with all the density profiles.

Figure 3 - (a) Extinction, which is proportional to density, estimated from simulated InSAR data assuming 0.1 dB/m (truth value in red) in the estimation process as a function of height above the ground. Also shown assuming 0.3 dB/m (green), and 0.6 dB/m (black); (b) relative profiles from (a), all normalized to peak of 1.0. Also shown is the unity normalized radar power profile, which is obtained by setting the peak extinction to zero, and is not ambiguous.



(a)

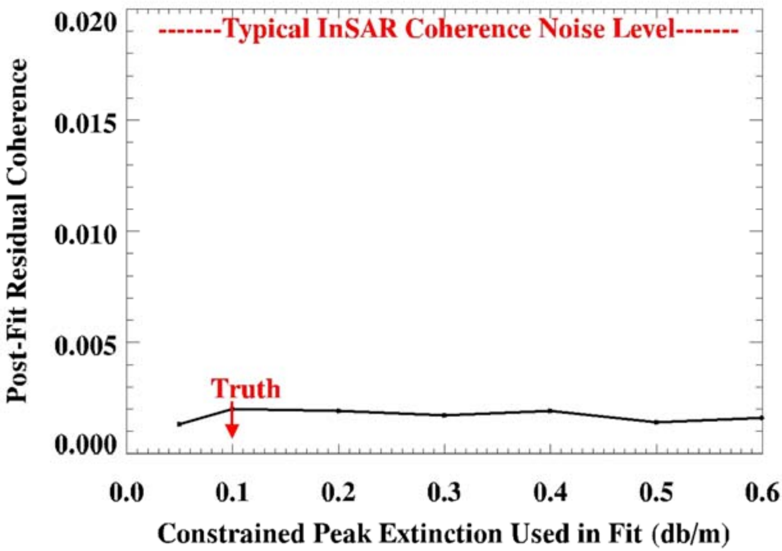


(b)

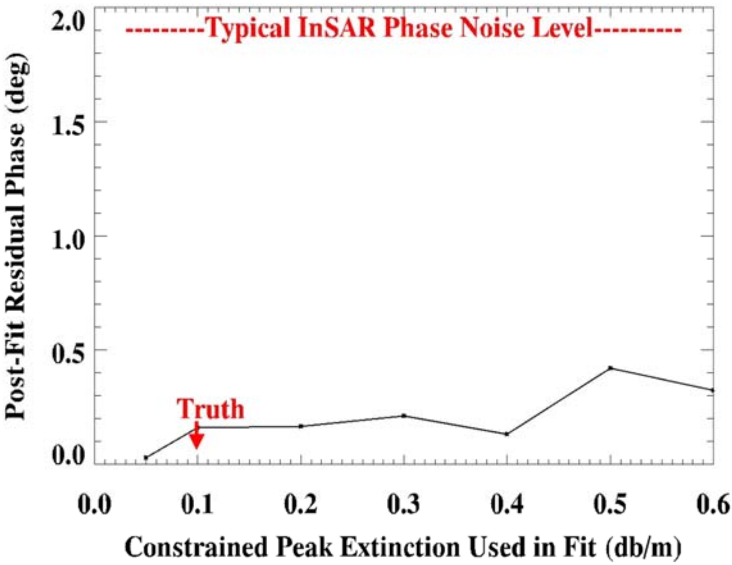
3. DETERMINING PEAK EXTINCTION OF INSAR-ESTIMATED PROFILES

In Figure 3, the peak extinction was constrained to three different values in the estimation process. For each of these values, a fit to the simulated data was performed. In each case, the twelve estimated density profile parameters can be used to generate complex coherences, which have both an amplitude—called the "coherence"—and a phase. The best-fit coherences can then be compared to the original simulated coherences to determine the so-called "post-fit residual", which is the difference between the simulated observations and those of the best-fit model. If the InSAR data were able to determine the peak extinction, we would expect the post-fit residuals to show a minimum near the "truth" value of 0.1 dB/m, and the depth of that minimum would have to be of the order greater than the typical coherence or phase noise level. Figure 4 shows that in fact this is not the case. It shows that the RMS difference between the best-fit coherence (4a) and phase (4b) as a function of constrained peak extinction does not increase appreciably as the constrained peak extinction moves away from the "truth" value of 0.1 dB/m. For the coherence, there is almost no difference resulting from changes in constrained peak extinction. All differences for coherence and phase are far less than the typical coherence noise level shown in red, suggesting that minimizing residuals in coherence by adjusting the peak extinction will produce ambiguous estimates of the peak extinction, or estimates with large uncertainties. Though there appears to be a slight rising trend in phase residuals in Figure 4b toward higher extinctions, the trend of a few tenths of a degree of phase is still much less than the typical noise level in phase of 2 degrees. At best, this rising trend means that the peak extinction could be estimated with an approximate +/- 0.5 dB/m error, far too large to be useful. The general conclusion of this simulation is that InSAR accuracies would have to be of the order of 0.001 in coherence and 0.1 degree in phase to estimate the peak extinction of a 12-parameter profile as described. These accuracies are smaller than the InSAR noise due to variations in the vegetation alone over reasonable (1 hectare) areas (speckle noise), suggesting that external data must be supplied for conversion of radar power density to vegetation density.

Figure 4 - (a) RMS post-fit residual coherence as a function of constrained peak extinction with the actual (truth) peak extinction at 0.1 dB/m indicated in red. (b) RMS post-fit residual phase versus constrained peak extinction. The fits are relatively insensitive to the value of peak extinction used—there is no perceptible minimum at the "truth" peak extinction—suggesting that InSAR data used to estimate profiles cannot estimate extinction. The typical coherence and phase noise in InSAR observations is shown in red, and is much higher than the depth of any perceptible minimum.



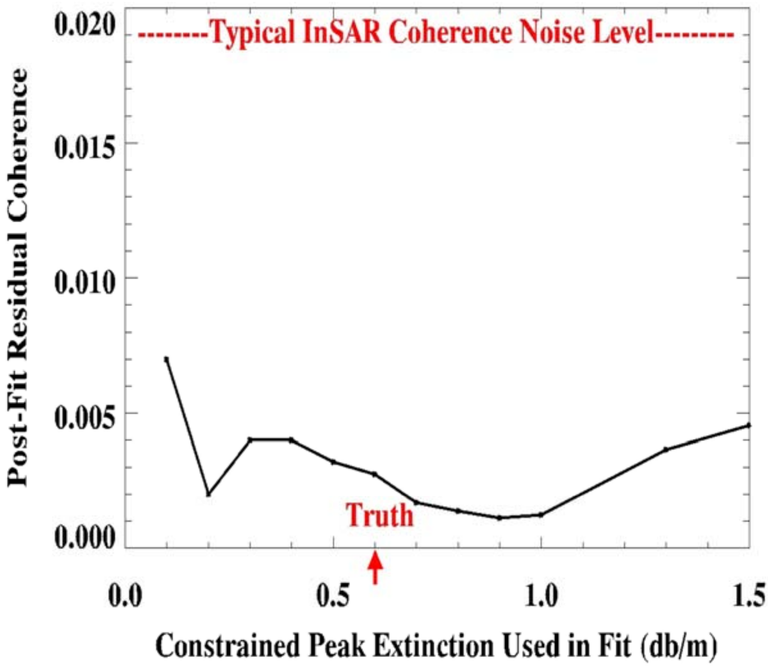
(a)



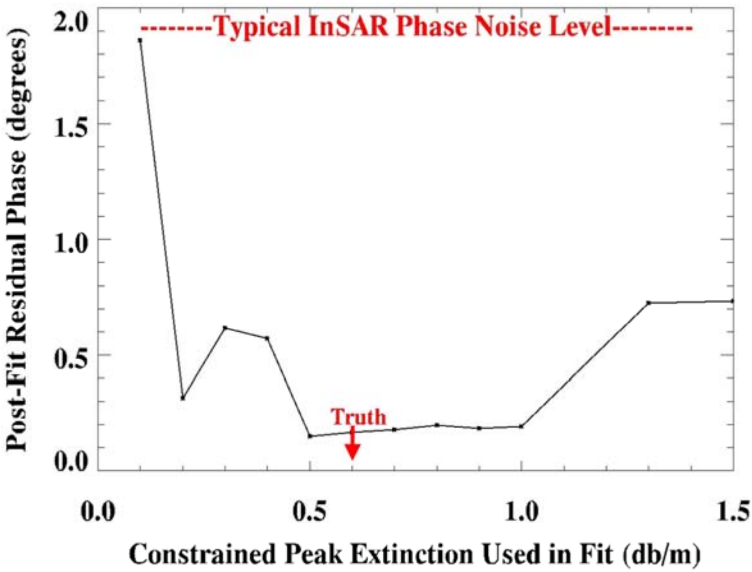
(b)

For the tropical forests of La Selva on which the simulation is based (TREUHAFT et al. in press), the peak value of 0.1 dB/m produced the best agreement with field and lidar relative density profiles for the real InSAR data. This value of 0.1 dB/m was surprisingly low for attenuation at C-band (CHUAH and KUNG, 1994), but it must be noted that this is an effective extinction and could be low due to gaps in the vegetation. It is also possible that instrumental losses in coherence could make the apparent forest penetration (marked by low coherence) greater than it actually is, which in turn would make the apparent extinction low. It is conceivable that, particularly for younger regenerating stands and in the absence of instrumental losses, the extinction could be higher. Therefore the entire simulation process was repeated for a "truth" extinction of 0.6 dB/m. The results are below in Figure 5. Again there is little sensitivity of residuals to the constrained value of peak extinction; there is no perceptible minimum at the "truth" value, although there does seem to be a minimum a little higher than the "truth" value. This might suggest that the 12-level parameterization of density is causing a biased estimate of peak extinction. But, again, because all dependences on constrained extinction are far below the error on coherence and phase, extinction does not appear susceptible to estimation from the InSAR data in the configuration of this experiment and analysis. Note that if simpler parameterizations of the vertical profile are used, for example if uniform (PAPATHANASSIOU and CLOUDE 2001) or Gaussian (TREUHAFT et al. 2002) profiles are assumed, then it becomes formally possible to estimate the extinction coefficient from polarimetric and/or multibaseline InSAR. The current analysis applies to arbitrarily complex profiles. The degree to which simpler profile structure can profitably be assumed is currently an open question.

Figure 5 – (a) RMS residual coherence of best-fit profile as a function of constrained peak extinction with the actual (truth) peak extinction at 0.6 dB/m (labeled by "Truth"). (b) RMS residual phase versus constrained peak extinction for "truth" peak extinction 0.6 dB/m.



(a)



(b)

4. CONCLUSIONS

This simulation suggests that while radar profile powers—obtained by setting the peak extinction to zero [see (1), (3), and (4) and Figure 3b]—can be unambiguously obtained from multibaseline InSAR. Estimation of the corresponding vegetation profiles requires external information which will constrain peak extinction. Very simple assumptions about peak extinction have produced good agreement with field and lidar profiles for tropical forests (TREUHAFT et al., in press), and it may be possible to devise general procedures for assigning peak extinction. The estimation of extinction was proposed (TREUHAFT et al., 1996) if forest canopies could be modeled simply, for example as uniform in height. It may still be possible to estimate extinction in those cases, but for tropical forests with complicated vertical structure, it is possible that in the estimation of profiles, external information will have to be supplied if more than the radar power profile is required. To date, it is not known whether the radar power profile itself may prove a robust indicator of biomass and other important ecosystem characteristics, obviating the need to estimate vegetation profiles. Radar power profiles have a direct analog in lidar power profiles, which are often used, without correcting for optical extinction, for estimating forest biomass (e.g.

DRAKE et al. 2002; LEFSKY et al. 2002). Two recommendations therefore emerge from this study regarding the production of profiles from InSAR: (1) multibaseline profiles from InSAR can either deliver radar power profiles for use in ecosystem characterization, or (2) simple rules can perhaps be developed for assigning peak extinction based on ancillary information, as was done for the data on which simulations in this paper were based (TREUHAFT et al., in press).

ACKNOWLEDGMENTS

The research described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

BALTZER, H. Forest mapping and monitoring with interferometric synthetic aperture radar (INSAR), *Progress in Physical Geography*, v.25, n.2, p. 159-177, 2001.

CHUAH, H. T.; KUNG, W. L. A microwave propagation model for estimation of effective attenuation coefficients in a vegetation canopy. *Remote Sensing of Environment*, v. 50, p. 212-220, 1994.

DRAKE, J.B. et al. Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment*, v.79, n. 2-3, p.305-319, 2002

HENDERSEN, F.M.; LEWIS, A.J. Radar fundamentals: The geoscience perspective. In: Ryerson, R.A. ed., Principles & Applications of Imaging Radar. *Manual of Remote Sensing*, 3. ed. New York, John Wiley & Sons, Inc., v.2, cap.3, p.131-181. 1998.

HOEKMAN, D.H.; QUINONES, M.J. Land cover type and biomass classification using AirSAR data for evaluation of monitoring scenarios in the Colombian Amazon, *IEEE Transactions Geoscience and Remote Sensing*, v. 38, n. 2, p.685–696, 2000.

LEFSKY, M.A. et al. Lidar remote sensing for ecosystem studies. *Bioscience,* v. 52, n. 1, p. 19-30, 2002.

Mac ARTHUR, R.H.; Mac ARTHUR, J.W. On bird species diversity. *Ecology* v. 42, n. 3, p. 594-598, 1961.

NARVAES et al. Evaluation of the interaction between SAR L-band signal and structural parameters of forest cover. In: *IEEE International Geoscience and Remote Sensing Symposium - Sensing and Understanding Our Planet –* IGARSS´2007. Barcelona, Spain, 23-27 Jul., 2007. [CDROM].

NEEFF, T. et al. Power spectrum analysis of SAR data for spatial forest characterization in Amazonia, *International Journal of Remote Sensing*, v. 26, n.13, p. 2851-2865, 2005.

PAPATHANASSIOU, K.P. and CLOUDE, S.R. Single-baseline polarimetric SAR interferometry, *IEEE Transactions on Geoscience and Remote Sensing*, v. 39, n. 11, p. 2352-2363, 2001.

RAUSTE, Y.et al. Radar based forest biomass estimation. *International Journal of Remote Sensing*, v.15, n.14, p. 2797-2808, 1994.

SANTOS, J.R. et al. Airborne P-band SAR applied to the aboveground biomass studies in the Brazilian tropical rainforest, *Remote Sensing of Environment*, v. 87, n.4, p.482-493, 2003.

TREUHAFT, R.N. et al. Vegetation characteristics and surface topography from interferometric radar. *Radio Science* v. 31, p. 1449–1485, 1996.

TREUHAFT, R.N. et al. Forest leaf area density profiles from the quantitative fusion of radar and hyperspectral data. *Journal of Geophysical Research,* v. 107, p. 4568–4580, 2002.

TREUHAFT, R.N. et al. Structure-based forest biomass from fusion of radar and hyperspectral observations. *Geophysical Research Letters* v. 30, p. 1472–1475, 2003.

TREUHAFT, R.N. et al . Estimating 3-dimensional structure of tropical forest from radar interferometry, *Ambiência*, v. 2, n.1, p.111-119, 2006.

TREUHAFT, R. N. et al., Vegetation profiles in tropical forests from multibaseline interferometric SAR, field, and lidar measurements, *Journal of Geophysical Research—Atmospheres*, [in press].

(Recebido em março de 2009. Aceito em junho de 2009).