Combination of an adaptive metamodel and a coherent polarimetric backscattering simulator for the characterization of forested areas at low frequencies

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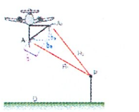
Abstract

A new method for forest characteristics inversion, based on a surrogate model derived from a full wave electromagnetic simulator using kriging techniques, is proposed. The feasibility of the method, is illustrated on a simple configuration for the forest where the polarimetric backscattering coefficients are used to retrieve both the age of the trunks and the ground moisture with different frequency bands. The benefit of polarimetry in this retrieval process is then studied.

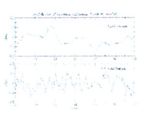
1 Model description

Radar parameters (illustration from CCT)



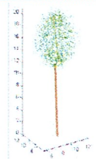
- frequency
- radar height
- baseline components: b_x, b_z
- resolution
- incidence angle

Soil parameters



- Root mean square height: h_{RMS}
- Correlation length: L_c
- Relative dielectric permittivity ε_r (via ground moisture m)

Vegetation parameters



Forest = a multi-layer environment with canonical elements:

- cylinders for trunks and branches
- ellipsoids for leaves
- Each layer described by:
  - its height
  - its number of trunk, branche and leave types
- Each type of scatterer defined by:
  - its size
  - its density
  - its eulerian angles distribution
  - its permittivity

Forest configuration – only 2 descriptive parameters

- Assumption: at low frequencies, trunks are the main scatterers,
- Allometric equations established for Nezer forest to determine the dimensions of the trunks (d and h) : $d = 0.169 \times \log(a) - 0.257$, $h = 56.618 \times d + 0.646$ with $a \in [10, 50]$ years
- Assumption: the vegetation moisture m_v is constant: 54%
- The m **ground moisture varies in** $[20-70]$% (related to the relative dielectric permittivity)
- Consider that the density is constant (managed forest)

Radar configuration

- Frequency $f \in [0.3, 2]$ GHz
- Incidence angle $\theta \in [20, 70]$ degree,
- Study of σ^0_{qp}, for all polarimetric channels.

2 Metamodel by kriging

Black-box model of the simulator

Model parameters $\mathbf{t} = [t_1, t_2, \dots, t_M]$ (can be controlled) . . . radar frequency (f) and incidence angle (θ)

Input parameters $\mathbf{x} = [x_1, x_2, \dots, x_N]$ (to be retrieved) . . . (forest age (a) and ground moisture (m))

Output data $y_{\mathbf{x}}(\mathbf{t})$ (can be measured or simulated) . . . (backscattering coefficients ($\sigma^0_{qp}(f,\theta)$))

Forward operator $\mathcal{F}\{\mathbf{x}\} = y_{\mathbf{x}}(\mathbf{t})$ – representation of the COSMO simulator, i.e., a function of the input and the model parameters (and, e.g., $y_{\mathbf{x}}(\mathbf{t}) = \sigma^0_{a,m}(f,\theta)$)

Approximation of $\mathcal{F}$ in two steps

1. Sampling: computation of n samples: $\mathcal{F}\{\mathbf{x}_i\} = y_{\mathbf{x}_i}(\mathbf{t})$, $i = 1, 2, \dots, n$ time-consuming but done only once
2. Interpolation by kriging: $\hat{\mathcal{F}}\{\mathbf{x}\} = \sum_{i=1}^{n} \lambda_i(\mathbf{x})\mathcal{F}\{\mathbf{x}_i\}$ fast, it is performed as many times as needed

Kriging for functional data

$$\hat{\mathcal{F}}\{\mathbf{x}\} = \sum_{i=1}^{n} \lambda_i(\mathbf{x})\mathcal{F}\{\mathbf{x}_i\} = \sum_{i=1}^{n} \lambda_i(\mathbf{x}) y_{\mathbf{x}_i}(\mathbf{t})$$

Two-level sampling:

"Upper" level: Choose $\mathbf{x}_{n+1}$ by the adaptive strategy

"Lower" level: Sample $y_{\mathbf{x}_{n+1}}(\mathbf{t})$, by using the same approach:

$$\hat{y}_{\mathbf{x}_{n+1}}(\mathbf{t}) = \sum_{i=1}^{k} \mu_i(\mathbf{t}) y_{\mathbf{x}_{n+1}}(\mathbf{t}_i) \quad \text{scalar kriging model}$$

Final database: $n \times k$ scalar samples:

$$\begin{array}{l} y_{\mathbf{x}_1}(\mathbf{t}_{11}), y_{\mathbf{x}_1}(\mathbf{t}_{12}), \dots, y_{\mathbf{x}_1}(\mathbf{t}_{1k}) \\ y_{\mathbf{x}_2}(\mathbf{t}_{21}), y_{\mathbf{x}_2}(\mathbf{t}_{22}), \dots, y_{\mathbf{x}_2}(\mathbf{t}_{2k}) \\ \vdots \\ y_{\mathbf{x}_n}(\mathbf{t}_{n1}), y_{\mathbf{x}_n}(\mathbf{t}_{n2}), \dots, y_{\mathbf{x}_n}(\mathbf{t}_{nk}) \end{array}$$

A simple illustration of kriging: one-variate polynomial function

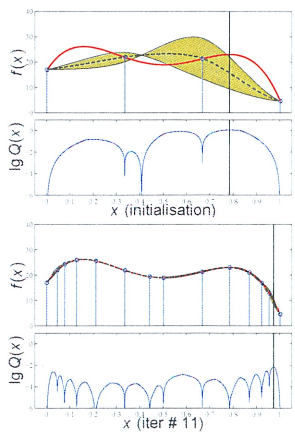
$$\hat{f}(x) = \sum_{i=1}^{n} \lambda_i(x) f(x_i)$$

- $f(x)$ modeled by a Gaussian random process
- n samples of f are needed
- Coefficients λ_i optimally chosen based on the covariance of the process
- $\hat{f}$ interpolates f, i.e., $\hat{f}(x_i) \equiv f(x_i)$

How to choose the sampling points $x_1, x_2, \dots, x_n$?

- Adaptive incremental sampling
- Next sample: the largest "improvement" of $\hat{f}$
- Auxiliary function $Q(x)$: space-filling + uncertainty reduction

$$x_{n+1} = \arg\max_{x \in X} Q(x)$$



—— : original function
– – – : kriging interpolation
filled area: "uncertainty"

3 Objective: To retrieve the age of the forest and the ground moisture

Numerical configuration

- Age = 40;
- m_v = 25%,
- $f \in [1, 2]$ GHz,
- $\theta \in [59-61]$ degree,

Interpolation error & Model of the "uncertainty"

$$\|\hat{\mathcal{F}}\{\mathbf{x}\} - \mathcal{F}\{\mathbf{x}\}\| = \sqrt{\frac{1}{(f_{\max}-f_{\min})(\theta_{\max}-\theta_{\min})} \int_f \int_\theta \left(\hat{\sigma}^0(\mathbf{x}) - \sigma^0(\mathbf{x})\right)^2 d\theta df}$$

where $\hat{\sigma}^0(\mathbf{x})$ the interpolated value and $\sigma^0(\mathbf{x})$ the exact one.

$$\Delta\sigma^0_{qp} = \sqrt{\frac{1}{(f_{\max}-f_{\min})(\theta_{\max}-\theta_{\min})} \int_f \int_\theta \left(\tilde{\sigma}^0_{qp} - \sigma^0_{qp}\right)^2 d\Theta df}$$

with δ the noise level and $\tilde{\sigma}^0_{qp}$ the measurement

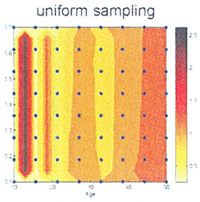
Caption

- $\Delta\sigma^0_{qp} < 1$ dB (Black),
- $\Delta\sigma^0_{qp} \in]1, 2]$ dB (Dark grey),
- $\Delta\sigma^0_{qp} \in]2, 3]$ dB (Light grey),
- $\Delta\sigma^0_{qp} > 3$ dB (White)

Results with $\Delta\sigma^0_{qp} < 1$ dB

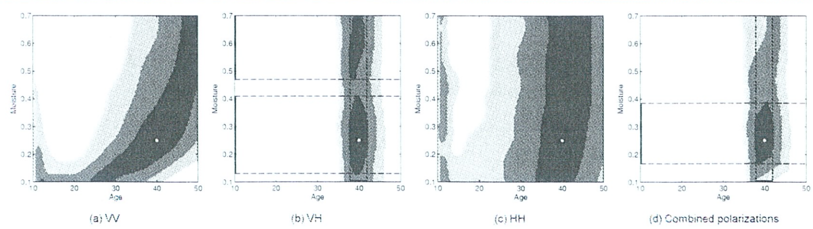
- Age in [37, 41] year
- m_v in [17, 39]% (combined polarizations)

Kriging interpolation example



• : initial samples   ∗ : sequentially added samples

Inversion using kriging metamodel (Error map)



(a) VV (b) VH (c) HH (d) Combined polarizations

4 Conclusion & perspectives

Conclusions

- The two-level adaptive sampling + kriging interpolator
  - provides acceptable accuracy
  - considerably reduces the computation time by replacing the simulator
- The surrogate model appears to be effective, as it can take into account:
  - the diversity of radar configurations (frequency, polarization, incidence angle)
  - the uncertainty on radar measurements

Perspectives

This work has been illustrated using σ^0_{qp} and a simple forest of trunks.

- the whole forest should be considered (more input parameters)
- additional outputs should be simulated
- the uncertainty on the forest parameters should also be taken into account