Soil Moisture Monitoring of Permafrost Active Layer over Arctic Tundra using PALSAR data

Nicolas Longépé, Takeo Tadono, Masanobu Shimada, and Hideyuki Fujii

Earth Observation Research Center (EORC)
Japan Aerospace Exploration Agency (JAXA)
Interaction of the cryosphere in the global climate system

LAND

ATMOSPHERE

OCEAN

Frozen ground
Permafrost

Snow Cover

Glaciers/Ice sheets

River and Lake Ice

Sea Ice

G.M.Flato published in Goodison et al., Cryospheric Systems, EOS Science Plan, 2000
Soil moisture monitoring using SAR data: an overview

• Frozen state detection
  – High permittivity contrast between frozen/thawed states

• Soil moisture retrieval method
  – Soil backscattering EM model is the core
    • Theoretical approaches: IEM, GO…
      – Wide range of validity
      – ACF, correlation length, multiple scattering modeling (HV) ?
    • Semi-Empirical models: Oh 92 and 2004, Shi 97…
      – Widely used mainly due to their simplicity
      – Extensive database
  – Inversion
    • Basic inversion method successful over well-controlled condition
      – Effects of vegetation, soil roughness variability, data calibration ?
    • Use of a priori information
      – Thornwaite monthly balance model by Mattia et al. 2006
      – Statistical assumptions by Verhoest et al. 2007

F. Mattia, et al.: Using a priori information to improve soil moisture retrieval from ENVISAT ASAR AP data in semiarid regions, TEEE TGRS, 2006
Case study: agricultural bare fields

Capabilities of full-polarimetric L-band SAR data for extracting cryospheric information?

- PALSAR/ALOS launched by JAXA in January 2006
  - Fully polarimetric radar images at L-Band
  - Over agricultural fields
PALSAR data analysis and simulation

EM simulation of shallow dry snow over frozen agricultural bare soil at L-band

Other vegetated areas

Shallow dry snow over frozen ground

Shallow wet snow

Shift -0.6 dB

Shift -1.75 dB

(σ_t^2 / σ_b^2) in dB

Histogram

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

0 -5 0 5 10 15

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Snow density

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4

Mv 12%

Mv 4.5%

Mv 1%

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Data analysis

• **Dry snow cover and soil permittivity drop-off in frozen state**
  – Secondary mechanisms decreases
    • EM effects are counterbalanced at co-polarized channels
    • Snow density enhance the HV drop-off
    • Confirmed by polarimetric analysis:
      – decrease of the entropy H, the alpha mean parameter or Freeman volume power

• **Difficult to implement a frozen state detection with PALSAR**
  – Large data variability
  – No strong difference between frozen/thawed states
  – Can be solved by means of a Support Vector Machine approach with polarimetric PALSAR data

• **Over this agricultural test site, no vegetation in winter**
  – Possibility to estimate the soil moisture
    • If soil roughness assessed before the first snowfalls

Polarimetric EM modeling and parameters inversion (1)

- Soil characteristics estimation (Nov. 2007)

**PALSAR DATA**
- Bare soil in Nov. 07
  - Co- and cross-polarization channels

**Soil inversion**
- Oh et al 2004

**Soil correlation length Optimisation with IEM**
- Co-polarization channels

\[ L_{\text{opt}}(\text{HH}) = 1.097 \times L_{\text{opt}}(\text{VV}) - 0.016 \]
\[ R^2 = 0.955 \]

\[ L_{\text{soil}} = 7.422 \times \sigma_{\text{soil}}^2 + 0.136 \]

- Reliably estimated soil correlation length for November 2007
- Soil moisture estimation confirmed by a hydrological model (Thornthwaite)

**Soil parameters**
- \( L_{\text{soil}} = 41.5 \text{ cm} \)
- \( \sigma_{\text{soil}} = 3.8 \text{ cm} \)
- \( L_{\text{soil}} = 34.4 \text{ cm} \)
- \( \sigma_{\text{soil}} = 2.8 \text{ cm} \)
• Residual liquid water estimation for frozen ground (Feb. 2008)
  – Spatially uniform dry snowpack: measured density 0.21
  – Soil roughness estimated in Nov. 2007
  – Local statistics optimization between EM simulation and PALSAR data
    • Chi Square statistic for co-polarization channel
    • Optimization on the soil moisture

✓ Residual soil moisture estimation seems realistic
Permafrost active layer over arctic tundra

Capabilities of PALSAR for extracting cryospheric information over wildland areas?

- Test site: the Arctic National Wildlife Refuge, Alaska
  - Covered by tundra vegetation (low shrubs, sedges, mosses..)
  - 8 full-polarimetric PALSAR acquisitions
Qualitative information (AMSR-E)

- **AMSR-E onboard Aqua**
  - Soil moisture product developed by Koike et al. 04
    - Based on PI (10.6GHz) and ISW (H at 10GHz – V at 36GHz)
    - Coarse resolution (depends on frequency) – sampling interval 9x10 km

✓ Good qualitative assessments: used as a priori information

EM simulations

- Oh’s models and PALSAR measurements

✔ Need for some enhancements (EM model ?)
Soil moisture optimization

• Some uncertainties
  – Regarding Oh’s weights
    \[ M_{V_{estim}} = \frac{\omega_1 M_{V_1} + \omega_2 M_{V_2} + \omega_3 M_{V_3}}{\omega_2 + \omega_3 + \omega_4} \]
    \[ M_{V_1} = f^{-1}(\sigma_{v_{hh}}, p) \]
    \[ M_{V_2} = g^{-1}(q, p) \]
    \[ M_{V_3} = h^{-1}(q, \sigma_{v_{hh}}) \]
  – Regarding PALSAR measurements combined with Oh’s models
    \[ \sigma_{v_{hh}}^0 = \sigma_{v_{hhPALSAR}}^0 (1 + \omega_{v_{hh}}) \]
    \[ \sigma_{v_{vv}}^0 = \sigma_{v_{vvPALSAR}}^0 (1 + \omega_{v_{vv}}) \]
    \[ \sigma_{v_{vh}}^0 = \sigma_{v_{vhPALSAR}}^0 (1 + \omega_{v_{vh}}) \]

• Optimization process
  – In case of snow, snow properties modify \( f, g, h \)
    • Snow dielectrically thicker than air
    • Permittivity contrast soil/air is reduced
  – Non-linear problem solved by an iterative Gauss-Newton algorithm
    \[ \text{Arg min}_{\omega_1 \rightarrow 6} \left| M_{V_{AMSR-E}} - M_{V_{estim}} \right|^2 \]
Soil moisture optimization

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    \[ \sigma_{vh}^0 = \sigma_{vh_{PALSAR}}^0 (1 + \omega_{vh}) \]

• Optimization results
  – Oh’s weights \( \omega_1 = 0.99 \quad \omega_2 = 0.54 \quad \omega_3 = 0.50 \)
    • Weights \( \omega_2, \omega_3 \) depend on \( q \) (VH/VV) which depends on correlation length
  – PALSAR optimization \( \omega_{hh} = 0.14 \quad \omega_{vv} = 0.10 \quad \omega_{vh} = -0.55 \)
    • Qualitative effect of vegetation by theory:
      – Additional anisotropic effect in cross-pol channel
      – Attenuation in co-pol channels

✓ Good adequacy between some theoretical concepts and optimized weights
Results (at local scale)

- Monitoring of the soil moisture

✓ Enhancement of the range of the estimated values
Preliminary results (at regional scale)

- Over frozen ground

12 March 2007

27 April 2007
Conclusion and outlooks

• Study case over agricultural fields
  – Soil roughness assessments before the first snowfalls
  – Inversion of a soil EM backscattering model during frozen states

• Over arctic tundra
  – Vegetation and other “unwanted” effects prevent from directly using bare soil EM model
  – Optimization process using AMSR-E soil moisture product
    • Counterbalance the vegetation effect and retrieve an “equivalent” bare soil

• Enhancements
  – Investigation on a more refined weighting system
    • Additive, multiplicative or non-linear effects on PALSAR data
  – Use of different EM models (IEM, …)
  – Resolution difference between PALSAR and AMSR-E