A RADAR-RADIOMETER SOIL MOISTURE ESTIMATION FRAMEWORK WITH ADAPTIVE REGULARIZATION AND JOIN PHYSICS

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Abstract

A unified framework for surface soil moisture estimation is presented in this work wherein both radar backscatter and radiometer brightness temperature measurements are effectively and simultaneously utilized. Within this combined estimation approach a regularization parameter is also introduced enabling the algorithm to perform radar-only, radiometer-only or joint radar-radiometer soil moisture retrieval when necessary. Through the use of numerical simulations, as well as field campaign data, the practicality and applicability of this new technique will be highlighted and two key features will be presented and discussed: (1) improved soil moisture estimation in a joint radar-radiometer framework (2) further reduction of estimation errors by utilizing the underlying physical relationships between emission and scattering. The latter exploits the joint physics of two measurement modalities within the retrial process.

1. Introduction

In an effort to further understand global water and carbon cycles as well as short and long term climate dynamics, NASAs Soil Moisture Active-Passive (SMAP) [1] mission aims to provide unprecedented global surface soil moisture estimates to the science community. To achieve numerous mission and science requirements, SMAP will employ two distinct, yet related, microwave remote sensing instruments. An L-band high-resolution Synthetic Aperture Radar (SAR) and an L-band Radiometer are utilized with the goal of estimating global surface soil moisture with a 3-day average repeat cycle., Improved soil moisture estimates are expected by effectively combining measurements from the SMAP radar and radiometer systems. However, due to the real aperture nature of radiometers and hence poor spatial resolution (~36km for SMAP), combining brightness temperature TB and radar backscatter σ^0measurements to address the SMAP requirements poses as a challenge. Therefore, a suitable soil moisture retrieval algorithm for SMAP must address two key issues (1) how to effectively combine radar and radiometer measurement within a single retrieval method and (2) how to address the spatial resolution difference between TB at 36km and σ^0 at 3-9km.

2. Background

A long heritage of soil moisture estimation algorithms and methods exists, however almost all methods rely on either radar backscatter or on radiometer brightness temperature. Empirical, semi-empirical and analytical [2-4] radar-only methods have in the past attempted to estimate surface soil moisture using polarimetric radar backscatter. Furthermore, time-series [5] and change detection [6] approaches have also been developed to retrieve surface soil moisture. Similarly, radiometer based estimation algorithms have also been widely used within the soil moisture community with the Single Channel Algorithm (SCA) [7], Dual Channel Algorithm [8] and the Land Parameter Retrieval Method [9] the most predominant algorithms of choice. The underlying theme amongst these existing methods is that they rely on radar-only or radiometer-only measurements, not both. In order to address the SMAP goals, recently efforts have been made to develop various "combined" radar-radiometer inversion algorithms. Most notably, the SMAP baseline approach [10] seeks to estimate soil moisture by first down scaling measured brightness temperature, i.e., "disaggregation," then attempts to estimate soil moisture using the SCA method. In this method, the value of radar backscatter measurements is only within the disaggregation process and not in the inversion process. Therefore the sensitivity of σ^0 to soil moisture and vegetation is not fully utilized.

The work presented here seeks to develop a foundation and framework for combined radar-radiometer soil moisture estimation techniques. That is, an effective and adaptive estimation algorithm is presented wherein both σ^0 and TB are combined to estimate soil moisture such that full advantage can be taken of the complimentary sensitivity of

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the two measurements to surface conditions and vegetation. Furthermore, this methodology applies not only to SMAP-like scenarios, but also directly to same-resolution measurements derived from tower-based or airborne systems. Note however that in this paper the discussion on brightness temperature disaggregation and spatial resolution disparity is not presented and the focus is on the inversion and estimation process. Therefore, it is assumed σ^0 and TB are observations of the same scene at the same resolution.

3. Soil Moisture Estimation Methodology

The methodology is a further continuation of the combined radar-radiometer retrieval algorithm initially developed in [11] which will further place emphasis on the need to joint physical forward modeling and adaptability. A joint cost function L(X) is set up which includes contributions from both radar and radiometer measurements such that they are constraint to each other. By doing so, the algorithm is capable of capturing the complimentary sensitivities of either measurement to soil moisture and vegetation. Furthermore, a regularization parameter γ is added to the cost function enabling the algorithm to shift between radar-only and radiometer-only contributions. The inclusion of this regularization parameter increases the adaptability and flexibility of the algorithm in order to find the best overall soil moisture estimates i.e. least retrieval errors. Mathematically the general form of the cost function is $L(\overline{X}) = L_a(\overline{X}) + \gamma \cdot L_p(\overline{X})$ where $L_a(X)$ and $L_p(X)$ are, respectively, the radar and radiometer contributions. More specifically, in a least squares format, L is

$$L(\bar{X}) = \frac{1}{2}\left[\gamma \cdot \sum_{pq=hh,vv}\left|\frac{\sigma^0_{pq} - \sigma^0(\bar{X})}{\sigma^0_{pq}}\right|^2 + \sum_{p=H,V}\left|\frac{TB_p - TB(\bar{X})}{TB_p}\right|^2\right] \quad (1)$$

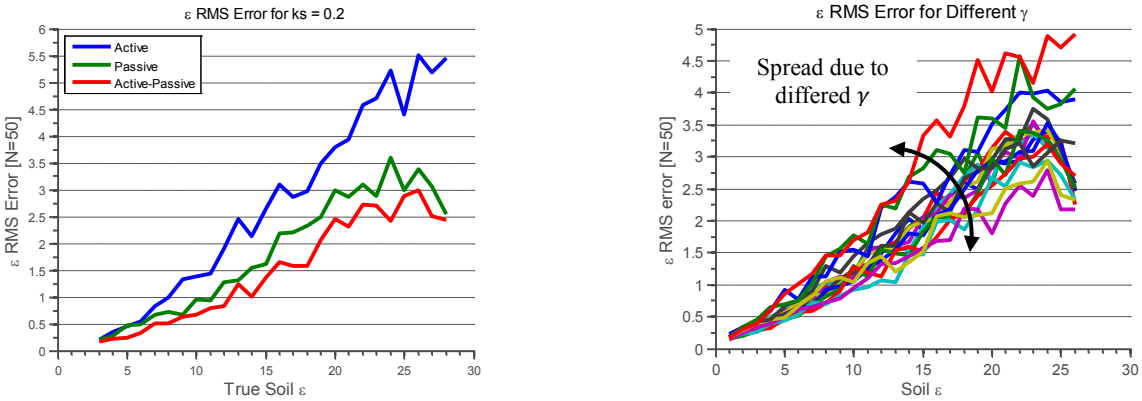
where σ^0_{pq} and TB_p are the respective radar backscatter cross-section and brightness temperature measurements at the same spatial resolution. $\sigma^0(\overline{X})$ and $TB(\overline{X})$ represent the radar scattering and radiometer emission forward models used within the optimization scheme. Note the dependence of the scattering and emission phenomena on the same set of underlying geophysical parameters $\overline{X}$. Specifically, $\overline{X}$ in this work is the unknown soil moisture of the scene under consideration and all other parameters are assumed known with some degree of uncertainty (vegetation water content, VWC, roughness, etc.). The optimum $\overline{X}$ which minimizes L(X) is reported as the retrieved soil moisture of interest. The tuning parameter γ is varied over a large range of values (10^{-3}-100) such that when $\gamma < 1$ more weight is given to brightness temeprture contrbutions and when $\gamma > 1$ more weight is given to radar backscatter contributions. By doing so the algorithm is capable of performing radar-only, radiometer-only or combined radar-radiometer estimation i.e. that is when contributing parts to the cost function are comparable. Therefore, the complimentary sensitivity of radar backscatter and brightness temperature to surface soil moisture, roughness and vegetation can be effectively captured, especially at soil moisture and vegetation extremes where scattering or emission may lose sensitivity. The optimum value for γ is selected such that overall retrieval errors over the range of soil moisture, roughness and vegetation are minimized. Currently, the global optimization technique known as Simulated Annealing [12] is used to minimize the cost function given in (1). The emission and scattering models of choice allow for rapid computation therefore the use of a global optimization technique can be justified. This optimization method for soil moisture retrieval has been successfully applied to radar-only soil moisture estimation for rough surfaces and vegetated regions in the past [13] [14].

For any pixel or region of interest, the modular structure of the algorithm allows substitution of forward scattering and emission models with ones which best describe the scene. Furthermore, the regularization term provides the flexibly to give more weight to the scattering model or emission model which again, best describes the phenomena under observation. The choice of forward models is critical and directly impacts the retrieval results. By linking emission and scattering through Peake's emissivity relationship [15] (hemi-spherical integration of the bistatic scattering cross-section) a so-called join-physics approach will be developed to take full advantage of scattering and emission responses to target features.

4. Results and Discussion

To demonstrate the feasibility of this algorithm, a series of numerical simulations are performed to retrieve soil moisture, i.e., soil dielectric constant, over bare and rough surfaces. The Kirchhoff emissivity relationship [16] as well as Peake's approach is utilized to highlight the potential of this method. Initially, for a moderately rough surface, k·s=0.2 at L-band, noisy radar backscatter and brightness temperature measurements are generated and then radar-only, radiometer-only and combined radar-radiometer estimation is performed. The Root Mean Squared (RMS) errors for 50 random noise iterations are then reported. In Figure 1.a, the retrieval RMS errors for the scenario outlined can be seen.

Note that the estimation is performed for soil dielectric constant and the conversion to soil moisture is assumed straight forward and not presented. With increasing soil dielectric constant, i.e. soil moisture, both radar backscatter and brightness temperature lose sensitivity therefore the increased retrieval RMSE is as expected. However, as seen in the figure, the combined radar-radiometer estimation scheme outperforms either of the radar-only and radiometer-only methods. Furthermore, the average RMS error, over the entire range of soil dielectric constant 3-30 (0.04-0.4 cm^3/cm^3 of soil moisture) is less than either method; 1.5 compared to 2.3 for passive and 3 for active in units of real dielectric constant. In Figure 1.b, the same radar-radiometer optimization scheme as in Figure 1.a is preformed and this time the value of γ is varied. The resulting estimation errors are affected based on the value of γ and for each γ a different RMS error over the range of soil moisture of interest can be seen, represented by the spread in Figure 1.b.

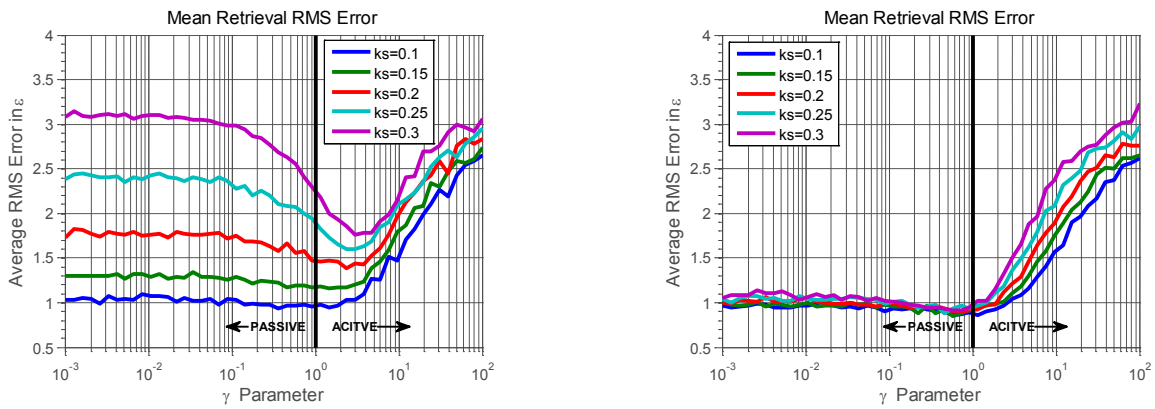


(a) (b)

Figure 1. Radar-only, Radiometer-only and combined Radar-Radiometer soil moisture estimation

To further clearly see the effects of γ on the retrieval process, the average RMS errors over the range of soil moisture is calculated and shown as a function of γ. The average error for each line in Figure 1.b is determined and plotted with respect to γ. This can be seen in Figure 2.a. The same process is also repeated for very smooth to very rough surfaces. At the extremes, radar-only or radiometer-only estimation is performed and in between joint estimation. Note that for rougher surfaces, as expected with the Kirchhoff approximation, radiometer-only estimation performs poorly. This is due to the model deficiency and lack of performance for rougher soils. On the other extreme, increased radar-only error is expected due to the lack of radar backscatter sensitivity for wetter soils. However, over the entire range of surface roughness, there exists an optimum point (γ~4) where the average error over the range of soil moisture has a minimum. The existence of this minimum highlights the power of this radar-radiometer retrieval method such that by finding the right balance between active-only and passive-only methods, overall retrieval errors can be minimized.

By applying the same approaches as in Figure 2.a and utilizing Peake's emissivity relationship improved and reduced retrieval errors are achievable. In Peake's approach the amount of expected emission is closely linked to the bistatic scattering cross-section of the target, therefore the emission and scattering phenomena are jointly related i.e. a joint-physical approach. By doing so, the retrieval algorithm is capable of completely utilizing the common sensitivity of either event to soil moisture and vegetation. Retrieval errors, in this approach are significantly reduces over the range of soil roughness and the results indicate the need for enhancements in both scattering and emission joint forward models to achieve best estimates.



(a) (b)

Figure 2. Average Retreival RMSE for Active-Passive rough surface retrial vs. γ for (a) disjoint models and (b) joint-physics.

5. Discussion

The extension of this work is to apply the same algorithm and approach to vegetated scenes. Extensive numerical simulations as well as test on field campaign data (tower-based and airborne data) will be performed to (1) present the cost function behavior and the effects of the regularization parameter, (2) demonstrate improved soil moisture estimation in a "true" active-passive framework, and (3) highlight the necessity for improved forward modeling especially the joint-physical approach in this new methodology.

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