TIME-SERIES RATIO ALGORITHM FOR NISAR SOIL MOISTURE RETRIEVAL

Jeonghwan Park[1,2], Rajat Bindlish[1], Alexandra Bringer[3], Dustin Horton[3], and Joel T. Johnson[3]

[1]NASA Goddard Space Flight Center, Greenbelt, MD 20771
[2]Global Science & Technology, Inc., Greenbelt, MD 20770
[3]ElectroScience Laboratory, The Ohio State University, Columbus, OH 43212

Email: jeonghwan.park@nasa.gov, rajat.bindlish@nasa.gov, bringer.1@osu.edu, horton.378@osu.edu, johnson.1374@osu.edu

ABSTRACT

The NASA ISRO Synthetic Aperture Radar (NISAR) mission is currently under development and will provide global L-band radar observations that will be helpful for various soil moisture applications. The final NISAR soil moisture product will have 200m spatial resolution with 12-day exact revisit time. A time-series ratio algorithm was implemented using NISAR simulated UAVSAR data collected during the SMAPVEX12 field experiment. In this paper, the performance of the time series ratio algorithm was assessed using *in situ* observations. Performance of the soil moisture retrieval algorithm was also assessed for dual polarization and quad-polarization observations modes.

Index Terms— NISAR mission, Soil Moisture, Time-Series Algorithm

1. INTRODUCTION

Soil moisture is a key climate parameter in Earth's terrestrial hydrology. Satellite remote sensing of soil moisture has advanced significantly over the last decade due to the success of the Soil Moisture and Ocean Salinity (SMOS) [1], [2] and Soil Moisture Active and Passive (SMAP) [3], [4] missions, both of which observe global L-band passive microwave measurements with 40 km spatial resolution, which limits their utility for "field-scale" (i.e. ~ 1 km spatial resolution) agricultural monitoring. The L-band frequency penetrates vegetated areas better than higher frequencies, so it is helpful in measuring soil moisture in mature agricultural sites. The desire for finer spatial resolution in the retrieval of soil moisture has motivated numerous studies of the use of high-resolution synthetic aperture radar [5], as well as other uses of SAR data to "downscale" other soil moisture products to finer spatial scales [6].

NISAR (NASA ISRO Synthetic Aperture Radar) mission will implement a sweep SAR mission that utilizes L-band (1.26 GHz, global coverage, up to 80MHz bandwidth) and S-band (3.2 GHz, limited coverage, up to 75MHz bandwidth) backscatter measurements for various remote sensing applications that is scheduled be launched in 2024 [7-9]. The NISAR mission will have a swath width of 240 km with a 12-day exact revisit sampling and a spatial resolution of 3-to-10-meter depending on the observation mode. NISAR's incidence angle will range from 34 to 48 degrees over the swath, and the fully polarimetric measurements are expected to achieve a noise-equivalent sigma-0 (NES0) of better than -20 dB. Currently, there is no fully operational soil moisture retrieval has been robustly demonstrated using L-band SAR measurements. SMAP radar observations were limited to 80 days and were not validated globally for different seasons. Thus, the NISAR mission will provide the first L-band product with finer spatial resolution (200m field-scale) compared to current satellite soil moisture missions including SMAP that may be of benefit for many applications.

2. TIME-SERIES RATIO ALGORITHM

The backscattered normalized radar cross section (NRCS) for a vegetated soil layer is a function of parameters related to soil, vegetation, and roughness, making the inverse problem of solving for soil moisture more difficult. A time-series ratio method assumes that the surface roughness and vegetation properties remain almost constant over two consecutive measurements [10-12]. Thus, the ratio of consecutively measured NRCS values at time and can be approximated as

$$\frac{\sigma_{PP}^{0}(t_2)}{\sigma_{PP}^{0}(t_1)} \approx \left|\frac{\alpha_{PP}(t_2)}{\alpha_{PP}(t_1)}\right|^2 \qquad (1)$$

where the alpha coefficient (α_{PP}) is the first-order scattering amplitude of the small-perturbation model (SPM) with PP (Either HH or VV) polarization, so that the ratio is a function of the dielectric constants of the soil and the incidence angle. This approximation works with dominant surface scattering but still works with surface-volume interaction term.

The time-series algorithm uses N NRCS observations to provide N-1 ratios. Increasing the number of samples used in the time series in the retrieval would obtain more accurate results for soil moisture, but it is more likely to include errors due to vegetation changes. In the NISAR mission, 3 days datasets (N=3: current, -12 days, and -24 days) could be considered for the matrix configuration based on these constraints.

$$\begin{bmatrix} 1 & -\sqrt{\frac{\sigma^0_{PP}(t_1)}{\sigma^0_{PP}(t_2)}} & 0 \\ 0 & 1 & -\sqrt{\frac{\sigma^0_{PP}(t_2)}{\sigma^0_{PP}(t_3)}} \end{bmatrix} \begin{bmatrix} |\alpha_{PP}(t_1)| \\ |\alpha_{PP}(t_2)| \\ |\alpha_{PP}(t_3)| \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

where t_1= -24days, t_2= -12days, and t_3= current. Finally, soil moisture could be inverted from the alpha coefficients using the Mironov dielectric model [13]. Figure 1 shows the relationship between soil moisture and alpha coefficients ($|\alpha_{HH}|$ and $|\alpha_{VV}|$) with various incidence angles from 30 to 50 degrees at clay fraction of 0.2. Both $|\alpha_{HH}|$ and $|\alpha_{VV}|$ are monotonically increasing functions regarding soil moisture values, but $|\alpha_{VV}|$ has better dynamic range than $|\alpha_{HH}|$.

The linear least-squares problem of the combined N-1 by N matrix equation is solved for the alpha coefficient at each time step. Since this matrix equation (2) is not fully determined, additional ancillary data should be incorporated to solve the problem. First, the maximum and minimum alpha coefficients derived from *in-situ* soil moisture information were used for alpha bounds constraints [14]. This method provides optimal performance but is not realistic for a mission since knowledge of maximum and minimum *in situ* information is needed. Second, the texture-based alpha maximum and minimum bounds were used as ancillary data and provided more generic form of the solution and showed acceptable performances [15]. Third, SMAP soil moisture climatology data was used to determine the monthly/bi-weekly soil moisture minimum and maximum bounds. Another approach is to utilize dual co-pol or cross-pol components instead of using minimum and maximum values from ancillary data sources. The performance of soil moisture retrieval using time series ratio algorithm using various approaches will be analyzed and compared in this presentation.

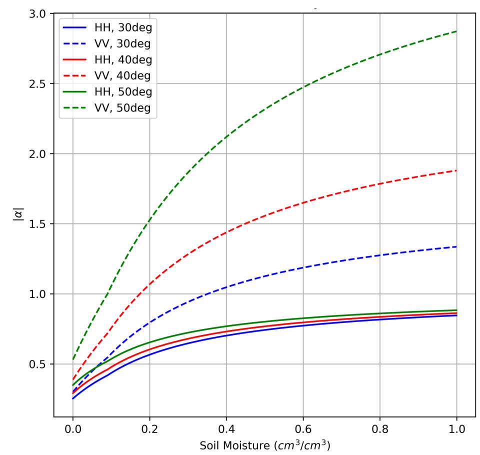

Figure 1. $|\alpha_{HH}|$ and $|\alpha_{VV}|$ with various incidence angles from 30 to 50 degrees. The Mironov model is used and cray fraction is fixed at 0.2.

3. RESULTS USING SMAPVEX12 UAVSAR DATA

For continued research into algorithm implementation and validation, datasets from the SMAP Validation Experiment 2012 (SMAPVEX12, Winnipeg in Manitoba, Canada) acquired using NASA's airborne L-band UAVSAR instrument have been analyzed [16]. The NISAR project re-processed the UAVSAR data for a NISAR-like configuration (HH 20MHz bandwidth and VV 5 MHz bandwidth) that was aggregated to 200m resolution (field scale) for soil moisture retrievals. Multiple UAVSAR flight lines between June 17 to July 17, 2012 were used for this analysis (11 days on flight line 31604 and 14 days on flight line 31606).

The key point of the time-series ratio algorithm using the alpha approximation is that the ratio of the consecutive backscatter measurements is identical to the corresponding alpha ratio from the model as shown in equation (1). However, due to error sources including rapid vegetation changes from the actual measurements, this relationship does not always hold. Figure 2 shows the relationship between the model and the measurement for several example sites. Figure 2 (a) and (b) present very good correlations at soybeans and wheat fields. However, some of the sites show a degraded relationship. Least square optimization processing provides a reasonable solution even though the one-to-one relationship is not perfect.

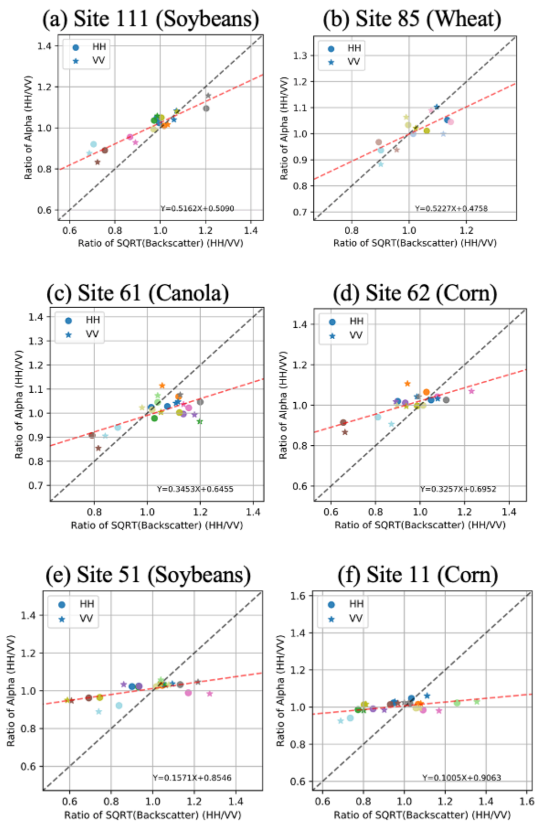

Figure 2. The relationship between consecutive backscatter measurement (HH and VV) ratio and corresponding alpha ratio. Example sites are (a) site 111 (soybeans), (b) site 85 (wheat), (c) site 61 (canola), (d) site 62 (corn), (e) site 51 (soybeans), and (f) site 11 (corn). All measurements from flight line 31606 and red dashed curve indicates the line fit.

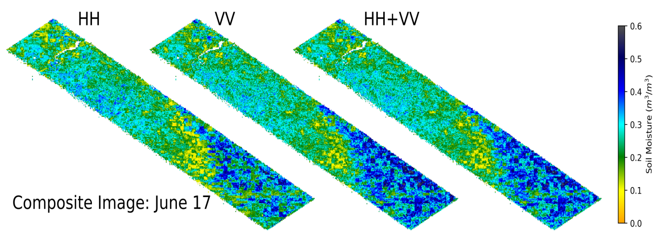

Figure 3. Estimated composite soil moisture images on June 17 (the first day of UAVSAR experiment) using the time-series ratio algorithm for HH, VV, and HH+VV configuration.

After solving the matrix equations with the alpha bounds, the retrieved soil moisture images were obtained for each polarization. Figure 3 shows the retrieved soil moisture images over the study areas on June 17, the first day of the UAVSAR experiment. Composite images were produced by combining soil moisture retrievals over the incidence range from both flight line (31604 and 31606). If two retrievals were available at a given pixel, the average value of two was represented. In addition to the use of only HH and VV polarization, the HH+VV method used a cost function modified by the combination of alpha HH and VV in soil moisture inverse processing. These images are like each other but have some small differences depending on the polarization combination used for the retrieval.

For the retrieval performances, the algorithm was assessed using *in situ* soil moisture information. Figure 4 provides scatter plots comparing retrieved values to those measured at *in-situ* sites using all 11 days of data for 31604 flight line. In the scatter plot, each crop type is marked with a separate color and symbol for comparison. It was found that the sites 101-105 contained standing water during the field experiment and were excluded from the comparisons. The statistics of the retrievals including correlation coefficient (R), bias, RMSE, and un-biased RMSE are indicated at the bottom of each figure. Retrievals show overall reasonable performances for all the methods. Especially, the method using HH+VV combination shows the best performance with the overall correlation of 0.732 and unbiased RMSE of 0.054 m^3/m^3. Also, VV performs better than HH because its alpha function shows better sensitivity to the soil moisture. In detail, the crop types of wheat, corn, and canola show overall reasonable performance. However, for soybeans, pasture, and broadleaf, the unbiased RMSE is higher than 0.060 m^3/m^3. More studies over agricultural areas with higher vegetation are necessary to verify these results.

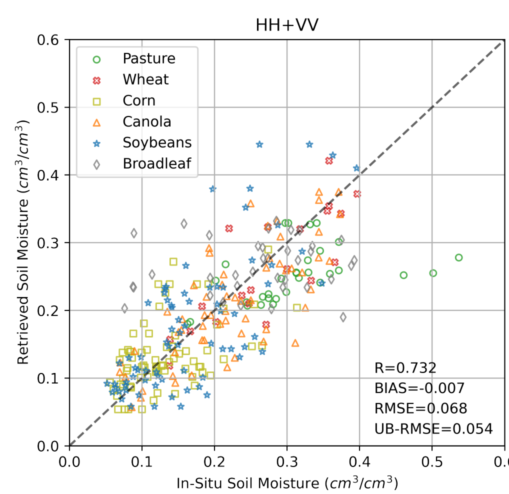

Figure 4. Scatter plots between in-situ soil moistures and retrieved soil moistures for HH+VV combination. (31604 Flight Line)

4. CONCLUSIONS

A time-series ratio method for soil moisture retrieval was successfully applied to the NISAR simulated SMAPVEX12 UAVSAR data. The method shows a reasonable performance with unbiased RMSE of 0.054 m^3/m^3 and appears suitable for use with NISAR mission. The method is advantageous since it does not require any forward modeling of the backscattered NRCS. Also, ancillary data dependence is minimal for soil moisture retrievals and there is minimal impact of uncertainties in ancillary data on soil moisture errors. More updates on the retrieval algorithms and results will be presented.

5. REFERENCES

[1] H. M. J. P. Barré, B. Duesmann, and Y. H. Kerr, “SMOS: The Mission and the System,” IEEE Transactions on Geoscience and Remote Sensing, vol. 46, no. 3, pp. 587–593, 2008.

[2] Y. H. Kerr et al., “The SMOS Mission: New Tool for Monitoring Key Elements ofthe Global Water Cycle,” Proceedings of the IEEE, vol. 98, no. 5, pp. 666–687, 2010.

[3] D. Entekhabi et al., “The Soil Moisture Active Passive (SMAP) Mission,” Proceedings of the IEEE, vol. 98, no. 5, pp. 704–716, 2010.

[4] S. K. Chan et al., “Assessment of the SMAP Passive Soil Moisture Product,” IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 8, pp. 4994–5007, 2016

[5] M. E. Hajj, N. Baghdadi, M. Zribi, and H. Bazzi, “Synergic Use of Sentinel-1 and Sentinel-2 Images for Operational Soil Moisture Mapping at High Spatial Resolution over Agricultural Areas,” Remote Sensing, vol. 9, no. 12, p. 1292, 2017.

[6] N. N. Das et al., “High-Resolution Enhanced Product Based on SMAP Active-Passive Approach Using Sentinel 1A and 1B SAR Data,” 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 2543–2545, 2017.

[7] P. Rosen et al., “The NASA-ISRO SAR (NISAR) Mission Dual-Band Radar Instrument Preliminary Design,” 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 3832–3835, 2017.

[8] NASA-IRSO SAR (NISAR) Mission Science Users’ Handbook, Version 1, revised April 3, 2018.

[9] NISAR Calibration and Validation Plan, V0.9, May 14th, 2018

[10] A. Balenzano, F. Mattia, G. Satalino, and M. W. J. Davidson, “Dense Temporal Series of C- and L-band SAR Data for Soil Moisture Retrieval Over Agricultural Crops,” IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 4, no. 2, pp. 439–450, 2011.

[11] A. Balenzano et al., "On the use of temporal series of L-and X-band SAR data for soil moisture retrieval. Capitanata plain case study", European Journal of Remote Sensing, vol. 46, no.1, pp. 721-737, October 2013

[12] J. D. Ouellette et al., “A Time-Series Approach to Estimating Soil Moisture From Vegetated Surfaces Using L-Band Radar Backscatter,” IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 6, pp. 3186–3193, 2017.

[13] V. L. Mironov, L. G. Kosolapova and S. V. Fomin, “Physically and Mineralogically Based Spectroscopic Dielectric Model for Moist Soils,” in IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 7, pp. 2059-2070, July 2009

[14] A. Bringer, J. Johnson, and R. Bindlish, "Predicting Soil Moisture Retrieval Performance for the NISAR Mission," 2020 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2020

[15] J. Park, R. Bindlish, A. Bringer, D. Horton, and J. Johnson, “Predicting Soil Moisture Retrieval Performance for the NISAR Mission,” 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), July 2021

[16] H. McNairn et al., "The Soil Moisture Active Passive Validation Experiment 2012 (SMAPVEX12): Prelaunch Calibration and Validation of the SMAP Soil Moisture Algorithms," in IEEE Transactions on Geoscience and Remote Sensing, vol. 53, no. 5, pp. 2784-2801, May 2015