Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 112 (2008) 403 – 414
Remote Sensing of Environment
www.elsevier.com/locate/rse

Appropriate scale of soil moisture retrieval from high resolution radar imagery for bare and minimally vegetated soils

D.P. Thoma [a,*], M.S. Moran [a], R. Bryant [a], M.M. Rahman [b], C.D. Holifield Collins [a], T.O. Keefer [a], R. Noriega [c], I. Osman [d], S.M. Skrivin [a], M.A. Tischler [e], D.D. Bosch [f], P.J. Starks [g], C.D. Peters-Lidard [h]

[a] *USDA ARS Southwest Watershed Research Center, Tucson, AZ, United States*
[b] *Saskatchewan Environment Planning and Risk Analysis Division, Regina, Canada*
[c] *NACCITEC, U.S. Army, Yuma Proving Ground, United States*
[d] *University of Arizona Space Grant Student, United States*
[e] *US Army Corps of Engineers Topographic Engineering Center, Alexandria, VA, United States*
[f] *USDA ARS Southeast Watershed Research Center, Tifton, GA, United States*
[g] *USDA ARS Great Plains Agroclimate and Natural Resources Research Unit, El Reno, OK, United States*
[h] *Hydrological Sciences Branch Code 614.3 NASA's Goddard Space Flight Center Greenbelt, MD, United States*

Received 27 October 2006; received in revised form 27 June 2007; accepted 29 June 2007

Abstract

This research investigates the appropriate scale for watershed averaged and site specific soil moisture retrieval from high resolution radar imagery. The first approach involved filtering backscatter for input to a retrieval model that was compared against field measures of soil moisture. The second approach involved spatially averaging raw and filtered imagery in an image-based statistical technique to determine the best scale for site-specific soil moisture retrieval. Field soil moisture was measured at 1225 m^2 sites in three watersheds commensurate with 7 m resolution Radarsat image acquisition. Analysis of speckle reducing block median filters indicated that 5×5 filter level was the optimum for watershed averaged estimates of soil moisture. However, median filtering alone did not provide acceptable accuracy for soil moisture retrieval on a site-specific basis. Therefore, spatial averaging of unfiltered and median filtered power values was used to generate backscatter estimates with known confidence for soil moisture retrieval. This combined approach of filtering and averaging was demonstrated at watersheds located in Arizona (AZ), Oklahoma (OK) and Georgia (GA). The optimum ground resolution for AZ, OK and GA study areas was 162 m, 310 m, and 1131 m respectively obtained with unfiltered imagery. This statistical approach does not rely on ground verification of soil moisture for validation and only requires a satellite image and average roughness parameters of the site. When applied at other locations, the resulting optimum ground resolution will depend on the spatial distribution of land surface features that affect radar backscatter. This work offers insight into the accuracy of soil moisture retrieval, and an operational approach to determine the optimal spatial resolution for the required application accuracy.
Published by Elsevier Inc.

Keywords: Radar; Soil moisture; Scale

1. Introduction

The distribution of near surface soil moisture is an important factor in hydrologic cycles, floods, climate, and ecosystem production. Resource managers can use such knowledge for a wide range of decision making related to prescribed burns, animal stocking rates, rangeland health and off road trafficability. Space based synthetic aperture radar (SAR) imagery can provide broad scale information on near surface soil moisture because radar signal return is responsive to changes in soil moisture. However, signal return is strongly affected by other variable surface features such as topography, roughness, and constructive and destructive wave interference that result in speckle inherent with active microwave systems (Mattia et al., 2003). To account for variable surface factors and image speckle, numerous approaches have been developed to derive estimates of soil moisture from imagery.

* Corresponding author.
E-mail address: dave_thoma@nps.gov (D.P. Thoma).

0034-4257/$ - see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2007.06.021

The methods designed to account for physical surface factors and radar geometry can be grouped into empirical, semi-empirical and physically based models (Baghdadi et al., 2004; Bindlish & Barros, 2000; Oldak et al., 2003; Shoshany et al., 2000) that account for surface feature influence on return signal by different means. However, regardless of retrieval method, imagery is typically filtered using one of several potential speckle reduction filters (e.g., Frost et al., 1982; Kuan et al., 1985; Lee et al., 1994). Most image filtering techniques are applied using relatively small (several pixels) moving windows and are evaluated in terms of image metrics without determining the relationship between filter window size and retrieval accuracy.

In spite of spatial filtering, even with high resolution imagery (1 to 25 m), studies have shown generally poor relationships existed between modeled and measured soil moisture at site (<1 ha) or field (1 to 10 ha) scales and only improved at broader watershed scales (>10 ha) (Kelly et al., 2003; Le Conte & Brissette, 2004; Thoma et al., 2006). The improvement in accuracy of soil moisture retrieval after filtering and at broader scales results largely from isolating central tendencies (i.e., average backscatter values) that are concealed by speckle at finer scales. Only the large pixel sample sizes associated with watershed scale allowed the central tendency in backscatter to be clearly related to surface features (Kelly et al., 2003). These and other researchers also showed that including a temporal component improves prediction results at finer scales (Oldak et al., 2003). But, this is unfortunate since many applications require relatively fine resolution (at site or field scales) soil moisture data at points in time.

Our hypothesis is that the central tendencies in radar backscatter and the appropriate scale for soil moisture retrieval can be determined through a combination of stepwise median filtering that reduces speckle and spatial averaging over increasingly larger areas to isolate central tendencies in image statistics. In this paper, we demonstrate a technique to determine the minimum level of filtering and spatial averaging necessary to determine backscatter with known confidence using an image-based approach.

The objectives of this research were to test these methods using field measurements and statistical analysis at multiple watersheds. The first step was to validate soil moisture retrieval from radar imagery using watershed scale validation sites in Georgia, Oklahoma and Arizona. Then, the proposed methods of filtering and spatial averaging were applied to images at the field scale and evaluated for speckle removal and signal enhancement. Finally, we demonstrated an image-based approach for determining an appropriate resolution for soil moisture retrieval at the site scale. This study offers a protocol for determining the minimum spatial resolution for soil moisture retrieval from radar imagery with known confidence.

2. Study areas and data sets

2.1. Study areas

The three study areas used in this research were the 150 km^2 Walnut Gulch (AZ) Experimental Watershed (31° 43′N, 110° 41′W) in southern Arizona, the 334 km^2 Little River (GA) Experimental Watershed (83° 40′W, 31° 36′N) in southern Georgia, and the 611 km^2 Little Washita (OK) Experimental Watershed (98° 3′W, 34° 52′N) in central Oklahoma, all operated by the United States Department of Agriculture, Agricultural Research Service.

The AZ Experimental Watershed is a semi-arid rangeland supporting low density grass and shrub vegetation (Renard et al., 1993). Soils are composed primarily of alluvium and contain 0 to 60% rock fragments by volume in the top 5 cm of soil profiles. The topography consists of rolling and heavily dissected terrain. Forty-two field sites were selected from grass and shrub dominated landscapes.

The GA Watershed is in a sub-humid coastal plain region that is heavily vegetated with a mixture of forest, crops, and pastures (Bosch et al., 2006). Slopes are gentle and soils are sandy with no rock fragments but may contain iron and manganese concretions less than 1 cm diameter near the soil surface depending on the extent of erosion. Twenty-two field sites were selected from among pasture and fallow row crop fields, and measurements were made when vegetation was senescent.

The OK Experimental Watershed is in a humid region dominated by forest and pasture land (Allen & Naney, 1991). Soils are composed primarily of wind deposited loess and residuum and the topography is gently rolling. Sixteen field sites were chosen within rested or actively grazed pastures, and like GA, measurements were made when vegetation was senescent. A single exception was a winter wheat field that experienced significant phonological change between image acquisitions.

2.2. Imagery

Radarsat images used in this study were F5F fine beam, 46° incidence angle, HH polarization, with 6.25 m resolution. This is one of 5 fine beam modes used in applications that require the highest spatial resolution (Radarsat International, 2000). At AZ, four images were acquired coincident with field measures of soil moisture in 2003 on 19 January, 30 July, 31 August, and 16 September. An additional image from 04 August 2002 was also obtained for AZ. At GA, images were acquired coincident with field measures of soil moisture in 2004 on 27 February, and 22 March. At OK, images were acquired coincident with field measures of soil moisture in 2004 on 19 February, 14 March, and 7 April. For the AZ, GA and OK study areas, one of the images was selected to represent ‘dry’ or ‘reference’ soil moisture conditions used in the delta index, described below. The reference images were acquired on 19 January 2003, 22 March 2003, and 19 February 2003 for AZ, GA, and OK respectively. Image resolution was rounded up to 7 m at import using nearest neighbor resampling and was georeferenced by matching clearly visible buildings and road intersections with 1 m resolution USGS digital orthophotographs. Registration error (RMSE) was kept below 4 m using between 26 and 44 ground control points.

2.3. Vegetation water content and biomass

Earlier research in the AZ watershed indicated that the sparse, rangeland vegetation there had little influence on radar