

Technical Note / Note technique

# Establishing a relationship between soil moisture and RADARSAT-1 SAR data obtained over the Great Basin, Nevada, U.S.A.

N.F. Glenn and J.R. Carr

**Abstract.** A predictive model estimating soil moisture with RADARSAT-1 data is developed for Winnemucca Lake, Nevada, in the western Great Basin of North America. Winnemucca Lake, a playa, is used for testing based on its hydrologic and geomorphic properties and its nonvegetated environment. The empirical model predicts soil moisture (%) as  $2.4 \sigma^0 + 137.8$  db, yielding a correlation coefficient between soil moisture and  $\sigma^0$  of 0.86. This relationship was developed by using block kriging to geostatistically register the point field soil moisture measurements to the  $\sigma^0$  values from the RADARSAT-1 pixels. It is considered to be significant because it depicts a new geostatistical approach for relating point measurements with area estimates of soil moisture from remote sensing data.

**Résumé.** Un modèle prévisionnel pour l'estimation de l'humidité du sol à l'aide des données RADARSAT-1 est développé pour la région de Winnemucca Lake, au Nevada, dans le grand bassin de l'Ouest de l'Amérique du Nord. Winnemucca Lake, qui est en fait une playa, est utilisé pour réaliser des tests à cause de ses propriétés hydrologiques et géomorphiques et de son environnement dénué de toute végétation. Le modèle empirique estime l'humidité du sol (%) sous la forme de  $2,4 \text{ sigma zéro } (\sigma^0) + 137,8$  db, donnant ainsi un coefficient de corrélation de 0,86 entre l'humidité du sol et  $\sigma^0$ . Cette relation a été développée en utilisant le krigéage par bloc pour ajuster géostatistiquement les mesures ponctuelles au champ d'humidité du sol aux valeurs de  $\sigma^0$  des pixels de RADARSAT-1. La relation est considérée significative étant donné qu'elle dépeint une nouvelle approche géostatistique permettant de relier les mesures ponctuelles avec les estimations de surface d'humidité du sol à partir des données de télédétection.

[Traduit par la Rédaction]

## Introduction

Soil moisture is a key parameter in a number of scientific models, including agricultural, hydrological, and climatic systems. Many models that use soil moisture data rely on point measurements from the field. However, point measurements typically cannot address the spatial and temporal variability inherent to soil moisture (Van Oevelen, 1998). Remote sensing can provide techniques to estimate soil moisture over large areas. This study focuses on establishing initial research and baseline conditions (field soil moisture, climate conditions, and soil type) for remote sensing of soil moisture in the Great Basin, Nevada, U.S.A. Water is an important, yet scarce resource for the Great Basin. This environment receives, on average, less than 25 cm of rain per year, yet sustains agriculture, wildlife, and urban communities. The key phrase here is "on average". Higher elevation regions, such as the Sierra Nevada Mountain Range, Toiyabe Mountain Range, and Ruby Mountain Range, receive over 100 cm per year in total moisture, mostly in the form of snow. Lower elevation regions, in particular graben floors, receive less than 10 cm total moisture annually. Thus, establishing a soil moisture study in this arid to semiarid environment is incredibly challenging, yet is important to managing water resources.

The objectives of this study include (i) investigating the sensitivity of RADARSAT-1 synthetic aperture radar (SAR) imagery to soil moisture under bare soil and minimal surface roughness conditions for two image acquisition dates in 1999; and (ii) investigating field sampling and image processing such that correlating point measurements in the field with averaged SAR measurements of soil moisture may be successfully utilized in subsequent models developed by the investigators.

## Site description

The study area is located on Winnemucca Lake, Nevada (40.06°N latitude, 119.37°W longitude) (**Figure 1**). Winnemucca Lake is a dry lake bed (playa) situated in the western portion of the Great Basin, east of Pyramid Lake, and is located 105 km northeast of Reno, Nevada. The field area

Received 15 March 2002. Accepted 18 September 2003.

**N.F. Glenn.**<sup>1</sup> Department of Geosciences, Idaho State University-Boise Center, 12301 W. Explorer Drive, Suite 102, Boise, ID 83713-1571, U.S.A.

**J.R. Carr.** Department of Geological Sciences, Mail Stop 172, University of Nevada-Reno, Reno, NV 89557-0138, U.S.A.

<sup>1</sup>Corresponding author (e-mail: glennanc@isu.edu).



**Figure 1.** Location of Winnemucca Lake, Nevada, Great Basin, U.S.A.

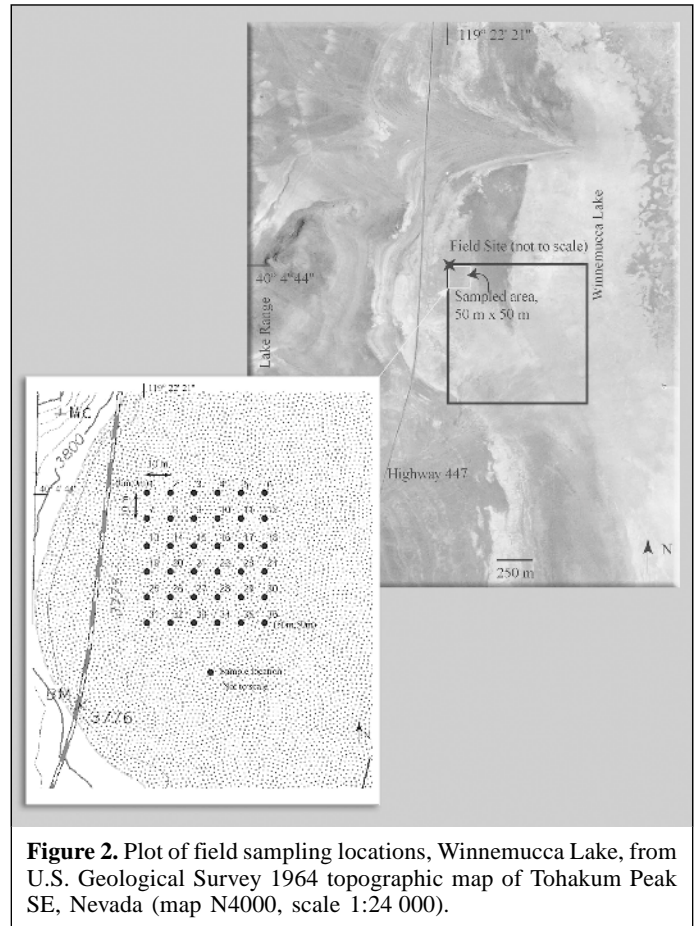
where sampling took place is approximately  $1 \text{ km} \times 1 \text{ km}$ ; a subdivided  $50 \text{ m} \times 50 \text{ m}$  area within this  $1 \text{ km}^2$  area is the main focus of the paper (**Figure 2**).

The Winnemucca Lake field area is a prime site to test the sensitivity of RADARSAT-1 to soil moisture because of its lack of vegetation, little topography, and uniform and minimal surface roughness characteristics. Because this site has little variability in surface roughness, both spatially and temporally, there is no need for filtering of surface roughness effects in the images.

The soils are fairly uniform throughout the field area and consist primarily of 2–3 cm of desiccated sandy silt overlying 7–10 cm of dry to moist sandy silt overlying moist to very moist silty clay. Moisture increases with depth, with a distinct change 3–5 cm below the ground surface.

## Synthetic aperture radar (SAR) data

Two RADARSAT-1 SAR images were acquired during the summer of 1999 (**Table 1**). The 30 July and 9 August 1999 images have pixel spacing of  $6.25 \text{ m} \times 6.25 \text{ m}$ , with approximate pixel resolutions of 10 m. The two SAR georeferenced fine (SGF) path images were processed as RADARSAT Committee on Earth Observation Satellites (CEOS) single-look images in both the azimuth and range directions.



**Figure 2.** Plot of field sampling locations, Winnemucca Lake, from U.S. Geological Survey 1964 topographic map of Tohokum Peak SE, Nevada (map N4000, scale 1:24 000).

**Table 1.** Specifications of acquired RADARSAT-1 images.

Date	UTC time	Image
30 July 1999	1358	Fine 2 (F2) beam mode, descending at an average incidence angle of $40.7^\circ$ (F2 beam mode has an incidence angle range of $39.3^\circ$ – $42.1^\circ$ )
9 Aug. 1999	0153	Fine 1 near (F1N) beam mode, ascending at an average incidence angle of $37.9^\circ$ (F1N beam mode has an incidence angle range of $36.4^\circ$ – $39.5^\circ$ )

## Ground-based measurements

### Field sampling

Soil samples were collected to relate field soil moisture conditions to radar response by the RADARSAT-1 satellite. The soil samples were collected on the two image acquisition dates, 30 July and 9 August 1999 between 1500 and 1900 UTC and 1300 and 1700 UTC, respectively.

Climate conditions were recorded for both dates of soil sampling and image acquisition. On 30 July 1999, the air temperature during sampling was approximately  $90^\circ\text{F}$  ( $32^\circ\text{C}$ ). Precipitation records indicated that rainfall had not occurred in

the area since the first week in June 1999, more than 50 days prior to the field collection day. On 9 August 1999, air temperature during sampling was approximately 70°F (21 °C). Precipitation occurred during the previous 3 days of field sampling, amounting to a total of 2.1 cm of rainfall between 30 July and 9 August sampling dates. However, no rainfall was recorded between the time of satellite collection and soil sample collection on 9 August 1999. Field sampling occurred within 1 h of satellite overpass on 30 July and within 11 h of satellite overpass on 9 August. The 11 h lapse between satellite collection and field sampling occurred overnight when temperatures were lower and relative humidity was higher. Consequently, the soil did not have ample opportunity to dry a significant enough amount to influence the relationship between field soil moisture and the radar response.

Soil moisture content of the grab field samples were determined by the oven-dried method in accordance with American Society for Testing and Materials (ASTM) standard test method D2216-90 (Bowles, 1992). The moisture content is defined here as the ratio of mass of water present in a soil mass to the mass of soil solids. Thirty-six soil samples were collected on each sampling date. The samples were collected 0–5 cm below the ground surface (bgs). The sampling locations were located 10 m apart in both the east–west and north–south directions in the northwest portion of the grid. The July sampling locations were revisited in August, with a 10 cm maximum distance between corresponding locations. Soil surface roughness was measured using a 1 m long bar leveled horizontally over the soil surface, after Griffiths and Wooding (1996). Average roughness measurements of less than 1 cm over five random 1 m transects were obtained in both the east–west and north–south directions in the field area. Note that the look angle of the RADARSAT-1 satellite is descending (west-looking) in the July image and ascending (east-looking) in the August image. This difference in orbits does not affect backscatter responses because the field area has little topography and surface roughness.

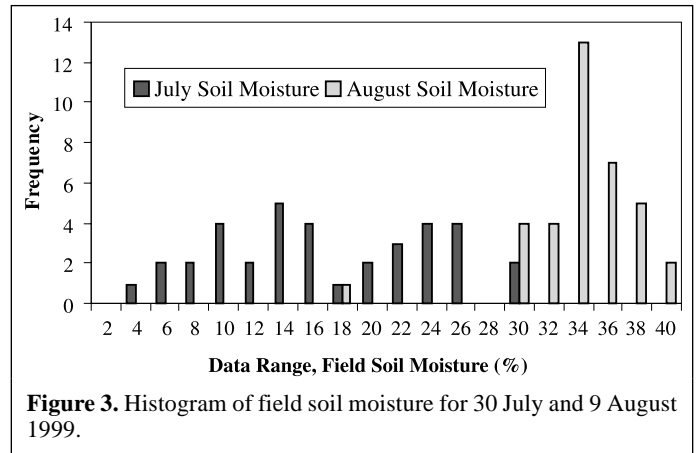
## Results and analyses

### Field data

The soil moisture values vary widely between the July and August sampling dates. The July data include soil moistures ranging from 3% to 29%, with a mean value of 16% and a standard deviation of 7.1% (Table 2; Figure 3). The July data were collected at a time when drying of the soil profile had occurred over an extended period of time (previous rainfall at this site occurred 54 days prior to data acquisition). It appears that the drying period caused a larger variability in the soil moisture for this particular field area. This is likely explained by the type of soil in the field area. The desiccated sandy silt most likely has lenses of finer grained material (silt and clay) that retained more moisture than other areas, resulting in inconsistent drying. The August data show less moisture variability. These data had a soil moisture content ranging from

**Table 2.** Statistical summary of July and August soil moisture and sigma nought ( $\sigma^0$ ) values.

	Field soil moisture (%)	RADARSAT-1 $\sigma^0$ (dB)
30 July 1999		
Mean	16.2	-50.8
Median	15.2	-49.8
Standard deviation	7.1	5.5
9 Aug. 1999		
Mean	33.8	-45.5
Median	34.0	-44.9
Standard deviation	3.8	5.9



**Figure 3.** Histogram of field soil moisture for 30 July and 9 August 1999.

17% to 39%, with a mean value of 34% and a standard deviation of 3.8% (Table 2; Figure 3). Overall, soil moisture values are more uniform than the July data, and this is attributed to the wetting period just prior to sample collection.

### Image processing

Both RADARSAT-1 images were georeferenced and resampled using nearest neighbor resampling. Ground control points were used to test georeferencing, and the RADARSAT-1 images were subset to the field area. Sigma nought ( $\sigma^0$ ) values, in decibels (dB), were calculated from beta nought ( $\beta^0$ ) for data analyses using the methodology described in Shepherd (1998):

$$\beta^0 = 10 \log_{10}[(DN^2 + A3)/A2] \quad (1)$$

$$\sigma^0 = \beta^0 + 10 \log_{10}(\sin I) \quad (2)$$

where DN is the RADARSAT-1 pixel digital number; A3 is the fixed offset from the radiometric data record; A2 is the look-up table (LUT) value, interpolated linearly; and  $I$  is the local incidence angle. The error associated with converting  $\beta^0$  to  $\sigma^0$  is approximately 0.4 dB (Shepherd, 1998), and the radiometric uncertainty (from the RADARSAT-1 radiometric data table) is approximately 1 dB (Canadian Space Agency, 1999a; 1999b). July 30, 1999,  $\sigma^0$  values range from -65.7 dB to -41.8 dB, with a mean of -50.8 dB and standard deviation of 5.5 dB; and

August 9, 1999,  $\sigma^0$  values range from  $-60.2$  dB to  $-39.0$  dB, with a mean of  $-45.5$  dB and standard deviation of  $5.9$  dB (Table 2).

### Data analyses

Statistical data analyses were performed with the subset RADARSAT-1 images and the 36 field-collected soil moisture samples from July and August 1999. The objective was to examine the relationship between field moisture and the RADARSAT-1  $\sigma^0$  values. Block kriging was used for geographical registration of field moisture values to the images.

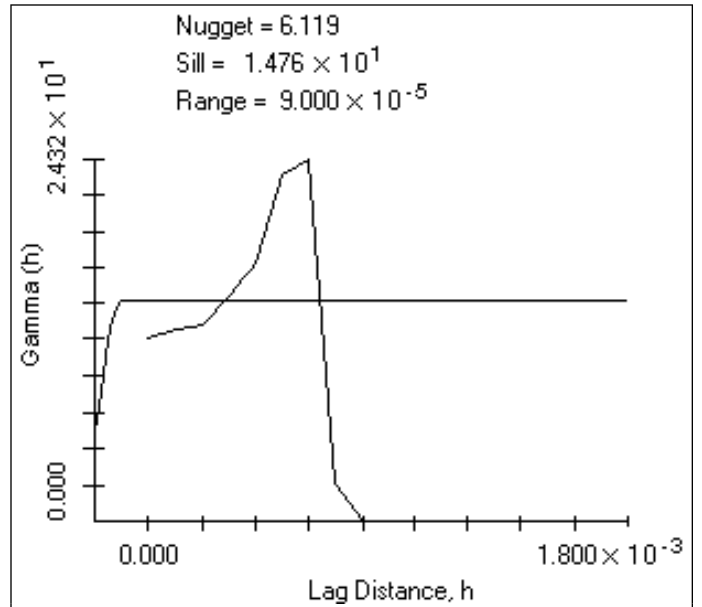
Kriging is a linear, least squares interpolation algorithm based on a weighted average algorithm of the form

$$Z^*(x_0) = \sum_{i=1}^N \lambda_i Z(x_i) \quad (3)$$

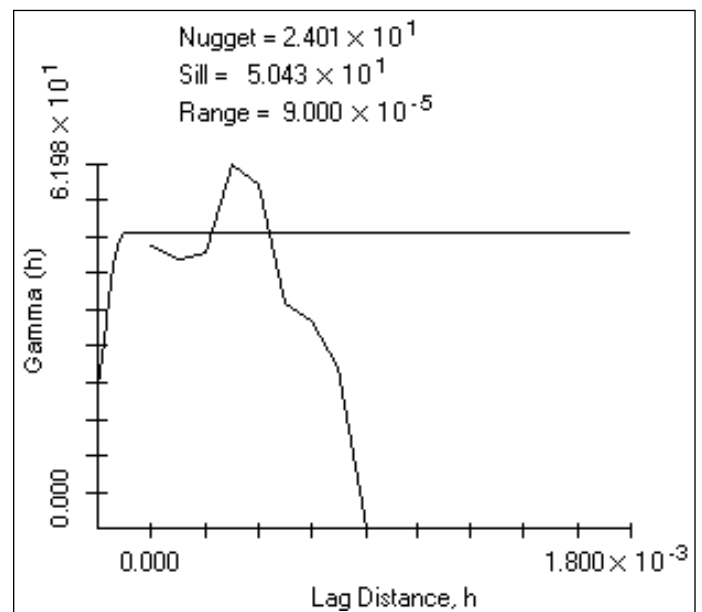
where  $Z$  represents spatial data, field-measured soil moisture, and RADARSAT-1  $\sigma^0$  values in the case of this study. This is a nearest neighbor algorithm, and thus  $N$  represents the closest number of field moisture values or  $\sigma^0$  values used for interpolation. In this study,  $N$  is set to 10 to minimize smoothing. The weights,  $\lambda$ , are based on spatial covariance, a function of distance between a known field sampling location or pixel location,  $x_i$ , and the location at which an interpolated value is desired,  $x_0$ . In block kriging, the interpolated value,  $Z^*(x_0)$ , represents an average over an area. Because pixel values also represent average reflectance or emittance over an area, block kriging is the preferred algorithm for their interpolation. Block kriging was applied using variograms for field moisture and  $\sigma^0$  values (Figures 4–7). These variograms indicate that a spatial correlation does exist for both field moisture and  $\sigma^0$  values. Consequently, the interpolation method, kriging, which relies on spatial correlation for prediction, is preferred over a more simple method, such as data averaging. More detail on the kriging method, along with software, is found in Carr (2002).

Scatterplots were developed for  $\sigma^0$  and kriged field soil moisture data for July and August (Figure 8). The July data show a positive linear correlation. The August data show little correlation within the dataset. A combined scatterplot of the July and August kriged data indicates a positive correlation between field and radar response (Figure 8). Moreover, the correlation coefficient ( $R$ ) between  $\sigma^0$  and field soil moisture is  $0.67$  and  $0.27$  for July and August, respectively, and  $0.86$  for the combined data (Figure 4).

Should there be concern about the use of only two points, July and August, in the regression, we emphasize that regression on the combined data mimics the July regression equation, indicating that the August data are modeled closely by the July regression. The authors note that additional data collection (i.e., image acquisitions) was prohibited because of image pricing.



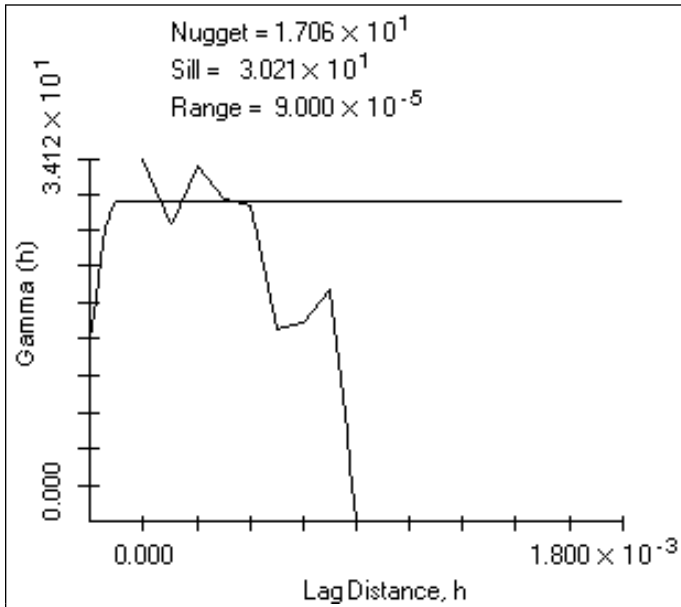
**Figure 4.** Semivariogram model for field soil moisture, 30 July 1999. The  $x$  axis is the lag distance  $h$  (in degrees latitude or longitude), and the  $y$  axis is the semivariogram value  $\gamma$ . Nugget is the value of  $\gamma$  associated with a zero lag distance; sill is the value of  $\gamma$  at the range; range is the lag distance at which  $\gamma$  becomes constant or begins to decrease.



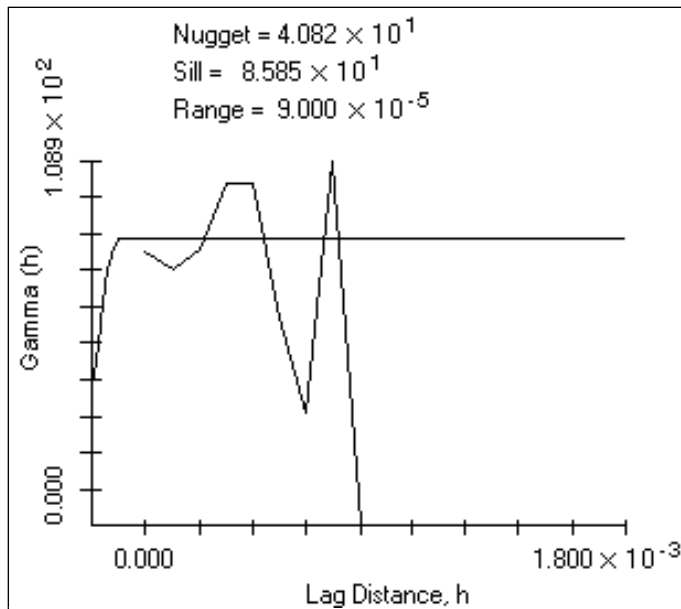
**Figure 5.** Semivariogram model for field soil moisture, 9 August 1999;  $x$  and  $y$  axes as in Figure 4.

## Conclusion

A significant finding in the regression analyses study results from analyzing both the July and August data simultaneously. The best-fit regression line occurs for the July and August data and, statistically, the  $R$  value is much higher than that for either

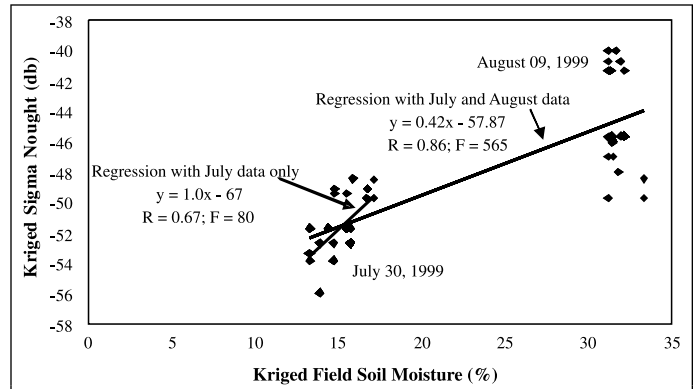


**Figure 6.** Semivariogram model for sigma nought, 30 July 1999; x and y axes as in **Figure 4**.



**Figure 7.** Semivariogram model for sigma nought, 9 August 1999; x and y axes as in **Figure 4**.

data set used alone. These results indicate scientific significance of the regression model because this model is perhaps the best yet obtained between satellite and field data, given the absence of other natural interferences, such as topography, surface roughness, and vegetation. Furthermore, the results indicate the ability of the radar to delineate and map moisture variability between images (temporally). Previous studies (Du et al., 2000; Baghdadi et al., 2002; Lu and Meyer, 2002; Moeremans and Dautrebande, 2000) have proved the opportunity of using SAR for soil moisture estimation with the development of complex models such as neural networks,



**Figure 8.** Regression analysis applied to kriged field soil moisture versus kriged sigma nought ( $\sigma^0$ ) values for 30 July and 9 August 1999.  $F$  represents the  $F$  statistic and reveals that this regression is statistically significant at better than 95% confidence.

interferometric coherence, and backscattering algorithms. This study identifies a simplified model using geostatistics for soil moisture retrieval given the absence of topography, surface roughness, and vegetation.

## Acknowledgements

The authors would like to thank the NASA-sponsored University of Nevada System Space Grant Consortium for providing funding for this project and RADARSAT International and the Canadian Space Agency for providing two RADARSAT-1 images through their Data for Research Use (DRU) program.

## References

- Baghdadi, N., Gaultier, S., and King, C. 2002. Retrieving surface roughness and soil moisture from synthetic aperture radar (SAR) data using neural networks. *Canadian Journal of Remote Sensing*, Vol. 28, No. 5, pp. 701–711.
- Bowles, J.E. 1992. *Engineering properties of soils and their measurement*. 4th ed. McGraw-Hill, Inc., New York.
- Canadian Space Agency. 1999a. *RADARSAT-1 scene ID M0190812*. [CD-ROM]. RADARSAT International, Richmond, B.C.
- Canadian Space Agency. 1999b. *RADARSAT-1 scene ID M0192431*. [CD-ROM]. RADARSAT International, Richmond, B.C.
- Carr, J.R. 2002. *Data visualization in the geosciences*. Prentice-Hall, Inc., Upper Saddle River, N.J.
- Du, Y., Ulaby, F.T., and Dobson, M.C. 2000. Sensitivity to soil moisture by active and passive microwave sensors. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 1, pp. 105–113.
- Griffiths, G.H., and Wooding, M.G. 1996. Temporal monitoring of soil moisture using ERS-1 SAR data. *Hydrological Processes*, Vol. 10, No. 7–12, pp. 1127–1138.
- Lu, Z., and Meyer, D.L. 2002. Study of high SAR backscattering caused by an increase of soil moisture over a sparsely vegetated area: implications for

characteristics of backscattering. *International Journal of Remote Sensing*, Vol. 23, No. 6, pp. 1063–1074.

Moeremans, B., and Dautrebande, S. 2000. Soil moisture evaluation by means of multi-temporal ERS SAR PRI images and interferometric coherence. *Journal of Hydrology*, Vol. 234, pp. 162–169.

Shepherd, N. 1998. *Extraction of beta nought and sigma nought from RADARSAT CDPF products*. Report AS97-5001 Rev. 2, Canadian Space Agency, Ottawa, Ont.

Van Oevelen, P.J. 1998. Soil moisture variability: a comparison between detailed field measurements and remote sensing measurement techniques. *Hydrological Sciences Journal*, Vol. 43, No. 4, pp. 511–520.