Can. J. Remote Sensing, Vol. 30, No. 3, pp. 560–565, 2004

Research Note / Note de recherche

Monitoring environmental indicators of vector-borne disease from space: a new opportunity for RADARSAT-2

S. Kaya, J. Sokol, and T.J. Pultz

Abstract. Environmental vector-borne diseases are plaguing much of the world and are a serious concern on a global scale. Many of these diseases are clearly associated with specific environmental conditions and landscape variables. The science and technology associated with remote sensing and geographic information systems (GIS) are suitable for identifying these environmental targets. Since vector-borne diseases are most often found in tropical environments and during rainy seasons with persistent cloud cover conditions, radar is an important sensor for monitoring and mapping the environmental indicators of disease. Preliminary investigations using RADARSAT-1 C-band horizontal transmit, horizontal receive (C-HH) imagery have proven especially useful for identifying wetland habitats and flooded areas. It is anticipated that the advancements associated with upcoming RADARSAT-2 sensors will improve the science of mapping vector-borne disease risk in tropical areas, particularly with access to increased spatial and temporal resolution and fully polarimetric data. This paper discusses the concept of using radar remote sensing for epidemiology applications, results using RADARSAT-1 for malaria risk mapping in coastal Kenya, and expected results with the advanced capabilities of RADARSAT-2.

Résumé. Les maladies à vecteur liées à des facteurs environnementaux affectent la plus grande partie de la planète et constituent une source d'inquiétude importante à l'échelle du globe. Plusieurs de ces maladies sont clairement associées à des conditions environnementales et des variables du paysage spécifiques. La science et la technologie associées à la télédétection et aux systèmes d'information géographique (SIG) nous permettent d'identifier ces cibles environnementales. Comme les maladies à vecteur se retrouvent le plus souvent dans les environnements tropicaux et durant les saisons des pluies dans des conditions de couvert nuageux persistant, le radar est un capteur important pour le suivi et la cartographie des indicateurs environnementaux de la maladie. Des recherches préliminaires utilisant des images C-HH de RADARSAT-1 se sont avérées particulièrement utiles pour l'identification des habitats en milieux humides et des zones inondées. Il est anticipé que les capacités accrues du capteur RADARSAT-2 à venir feront progresser la science de la cartographie des risques de maladies à vecteur dans les zones tropicales, en particulier grâce à la plus grande résolution spatiale et temporelle proposée et à l'accès aux données polarimétriques. Cet article aborde le concept de l'utilisation de la télédétection radar dans le contexte des applications épidémiologiques, de même que les résultats de l'utilisation de RADARSAT-1 pour la cartographie des risques de malaria dans les zones côtières au Kenya et les résultats attendus des capacités améliorées de RADARSAT-2.
[Traduit par la Rédaction]

Introduction

Many environmental diseases are carried and transmitted by a disease "vector" (e.g., the *Anopheles* mosquito is the vector for malaria). These vector-borne diseases are most often prevalent in areas with specific environmental conditions conducive to vector breeding. With this direct link to the environment, space-borne remote sensing technology may be used to identify breeding grounds and relate these targets to areas populated by the disease host (e.g., humans are the host in the case of malaria) (Hay, 2000; Hay et al., 1998; Hugh-Jones, 1989; Thomson et al., 1997; Washino and Wood, 1993).

With nearly one half of the human population inhabiting areas where they are at risk of one or more vector-borne diseases (World Health Organization, 1998), an effective surveillance tool is required to identify populations at risk and timing of potential risk. Strategic assessment of areas at risk of a vector-borne disease will facilitate rapid action by those in charge of mitigation and control initiatives, such as targeted pesticide application or distribution of medication (Hay et al., 1998). Information extracted from remotely sensed data (such as the presence of water, required for breeding) can often provide critical input to decision-making processes by health organizations around the world.

Although the concept of using satellite-based mapping techniques for surveillance of disease is not new (Woodzick and Maxwell, 1977; King, 1979; Wagner et al., 1979; Hayes et

---

Received 6 June 2002. Accepted 26 January 2004.

S. Kaya, J. Sokol,[1] and T.J. Pultz. Canada Centre for Remote Sensing, Natural Resources Canada, 588 Booth Street, Ottawa, ON K1A 0Y7, Canada.

[1] Corresponding author (e-mail: jennifer.sokol@ccrs.nrcan.gc.ca).

al., 1985; Jovanovic, 1987), the use of radar remote sensing technology has not been extensively explored by the health community (Hay, 2000). This may be related to the limited amount of commercially available radar image data in the past and the perceived complexity associated with radar data interpretation and analysis. Further, early space-borne radar sensors have had limited sensor configurations (C-band vertical transmit, vertical receive (C-VV); incidence angle $\theta = 23°$) for many applications. The current generation of radar satellites, however, including Canada's RADARSAT-1, the European environmental satellite (Envisat), and Canada's future RADARSAT-2, are changing this trend. Since many infectious diseases are prevalent in tropical areas with substantial cloud cover, it is often difficult to obtain useful cloud-free satellite data from commonly used optical sensors. Radar offers a solution to this with its capability to penetrate clouds and haze and to image both day and night. This "all-weather" capability makes satellites such as RADARSAT-1 useful tools for surveillance in tropical areas. RADARSAT-2 will build on this capability by offering higher resolution data, both spatially and temporally, and fully polarimetric C-band imagery.

In this paper, we discuss the potential of RADARSAT-1 for wetland mapping and associated potential risk of vector-borne disease environments, with a case study on malaria risk assessment in coastal Kenya. This effort demonstrates the capability of radar remote sensing for vector-borne disease monitoring and assesses the potential of RADARSAT-2 for the future.

Results using RADARSAT-1 for malaria risk mapping in coastal Kenya

Beyond radar's primary advantage of all-weather capability, synthetic aperture radar (SAR) also has particular application to vector-borne disease monitoring because of its sensitivity to surface moisture conditions and target geometry. C-band horizontal transmit, horizontal receive (C-HH) SARs, such as RADARSAT-1, have been found to be a suitable tool for mapping flood area extent, wetland regions, and flooded forest areas (Crevier and Pultz, 1996a; Costa et al., 1997; Ramsey, 1995; Pope et al., 1997).

As a demonstration project, multitemporal standard mode (S7) RADARSAT-1 data were collected over a study site in coastal Kenya, near the town of Mombasa, in 1999 and 2001 during both wet and dry seasons. The area is home to two thirds of the rural population of coastal Kenya, where malaria is a severe health concern (C. Mbogo, Kenya Medical Research Institute, personal communication, 2001). The environment mainly consists of a mix of indigenous forest, grassland savanna, mangrove swamps, and wetland vegetation. Plantation agriculture (mainly coconut, sisal, and cashews) is also found along the coast. The ground elevation ranges from sea level to approximately 400 m above sea level (asl), and there are several small rivers that flow from the highlands to the Indian Ocean.

Mosquito larval habitats in this area are associated with wetland areas and flooded vegetation, although these sites are diverse and change with the season. Coastal Kenya has two rainy seasons: from April to June and from October to November. Mean annual precipitation differs greatly in different parts of the coast, from over 1200 mm just inland from Mombasa, to less than 750 mm on the western border of the inhabited area. During the dry season, some rivers and streams become completely dry, while others have reduced flow and numerous isolated, residual pools of water in the main riverbed. The wetland areas, both seasonal and permanent, are of particular importance to mapping malaria in the region (Hugh-Jones, 1989; Washino and Wood, 1993; Beck et al., 1994; 1997; Thomson et al., 1997).

Figure 1 summarizes the methodology used for the research discussed here, including data input, geometric correction, image filtering, classification, and analysis. The four standard mode images were coregistered and filtered using a mean filter (9 × 9 window), and a texture analysis was performed, as this has been used successfully in wetland studies (Arzandeh and Wang, 2002). The filtered and texture-analysed images (total of eight images) were used as input to the classification routine. An object-oriented approach to image classification was used (eCognition software, Definiens Imaging DmbH, Munich, Germany) to segment the images into homogeneous objects and classify these objects into six primary classes: water, grassland, wetland, populated areas, indigenous forest (mainly mangrove), and rain forest (PCI Geomatics Enterprises Inc., 2001). This procedure was carried out using land cover training areas, which were verified by scientists in the field (10–15 training polygons per class). An accuracy assessment of the results, using additional known land cover sites as test areas (10 test polygons per class), showed an overall classification accuracy of 85.5%, with varied accuracies for individual classes. **Table 1** shows the confusion matrix for the object-oriented classification.

For the purpose of this research project, the flight range (i.e., distance to infect) of the *Anopheles* mosquito is estimated to be 2 km from the larval breeding site (Washino and Wood, 1993; Beck et al., 1994; 1997). With this information as a baseline, a proximity analysis was carried out whereby classified wetland parcels were extracted from the classified image and integrated as a layer on the original RADARSAT data. Similarly, areas that were classified as populated were also extracted. A buffer zone routine created a 2-km region around the wetland areas, and a proximity analysis allowed for extraction of the populated areas that were found within the buffered zone. The result of this methodology produced a malaria risk map, indicating the populated areas at risk of malaria infection. This sequence of activities is shown in **Figure 2**. The final risk map shows that nearly 98% of the populated areas are in fact located within a 2-km proximity to potential malaria-carrying mosquito breeding grounds.

The results of this research indicate the potential of radar remote sensing for classifying land cover, specifically as environmental variables relate to malaria vector breeding

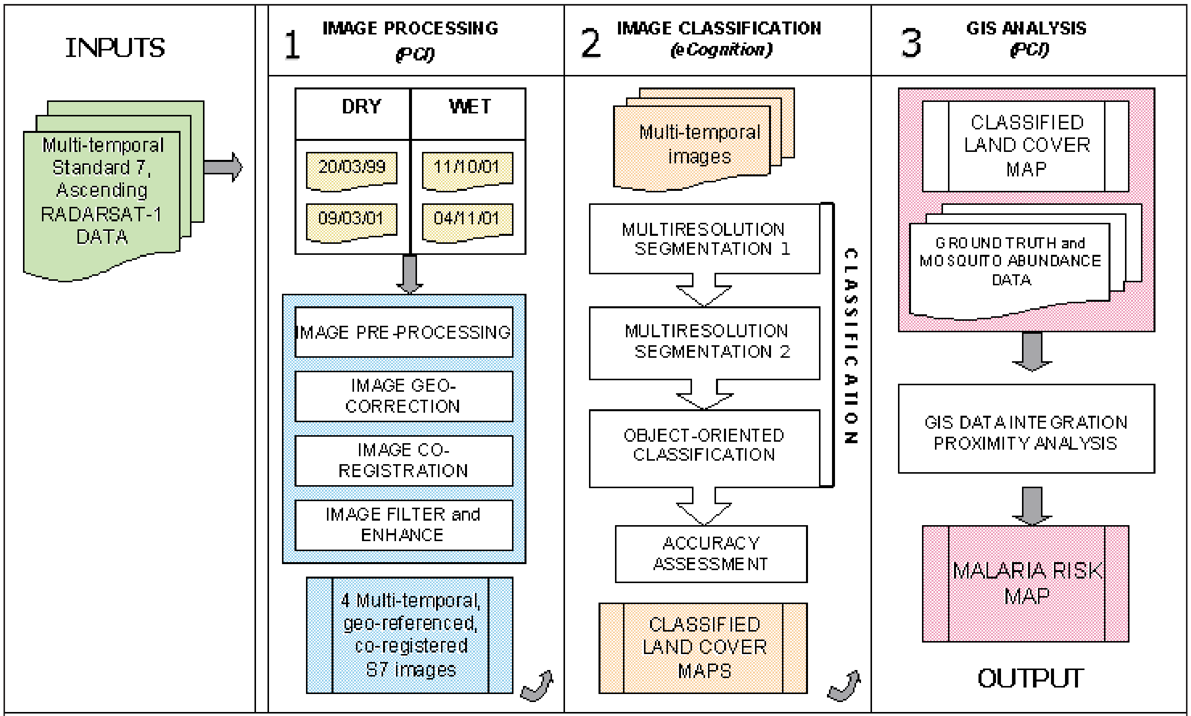

Figure 1. Summarized methodology for malaria risk mapping in coastal Kenya using multitemporal standard mode RADARSAT-1 imagery.

Table 1. Confusion matrix showing accuracy assessment of object-oriented classification (in pixels).

Reference class	Water	Wetland	Grassland	Forest 1	Forest 2	Agriculture	Populated	Sum
Water	17 514	0	0	0	0	0	0	17 514
Wetland	0	2355	0	3 484	0	571	0	6 410
Grassland	0	0	22 065	0	0	0	0	22 065
Forest 1	0	1249	0	10 375	0	1044	0	12 668
Forest 2	253	0	612	0	6343	1299	0	8 507
Agriculture	0	0	0	0	2086	3400	0	5 486
Populated	0	0	0	0	0	0	1034	1 034
Unclassified	0	0	0	0	0	0	75	75
Sum	17 767	3604	22 677	13 859	8429	6314	1109	
Accuracy								
Producer	0.986	0.653	0.973	0.749	0.753	0.538	0.932	
User	1.000	0.367	1.000	0.819	0.746	0.620	1.000	
Kappa	0.981	0.620	0.961	0.696	0.720	0.501	0.931	
Overall accuracy	0.855							
Overall kappa	0.818							

grounds. Confusion in the classification results was seen with the wetland and mangrove forest classes, which can be explained by the similar target geometry and moisture conditions of the two classes, causing the radar backscatter signatures to have a limited separability. Both classes have suitable environmental characteristics of malaria vector breeding grounds, and further investigation will combine wetland and mangrove land cover classes to produce a more accurate classification for input into a risk mapping routine.

Opportunities for RADARSAT-2

The capabilities of RADARSAT-1 will be further enhanced with RADARSAT-2, which will provide all the imaging modes of RADARSAT-1 and some new modes that incorporate significant innovations and improvements. Hence, the satellite will offer data continuity to RADARSAT-1 users and new data that will support development of improved and new applications. The new capabilities associated with RADARSAT-2 that will be of particular significance to disease monitoring efforts are high-resolution imaging, right- and left-looking geometry, and fully

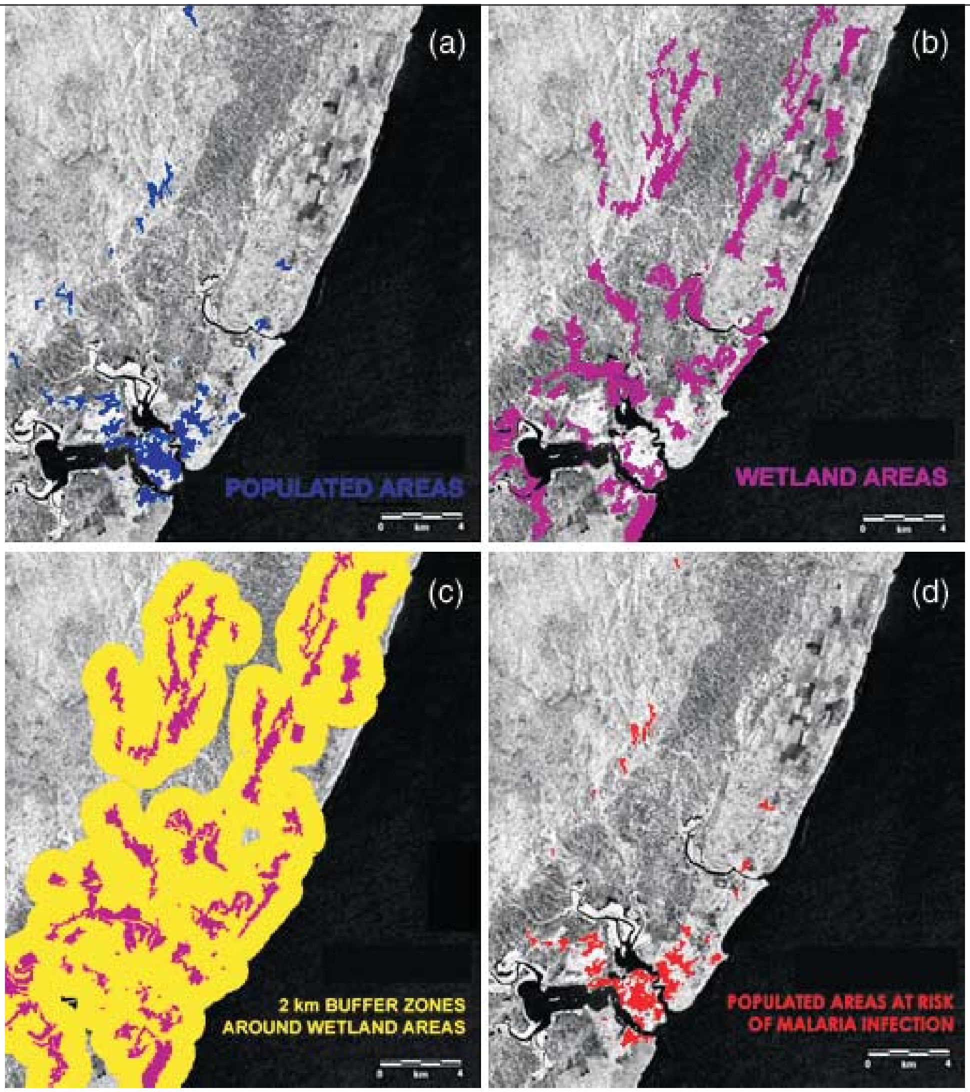

Figure 2. RADARSAT-1 standard 7 image with areas classified as (a) populated, (b) wetland areas, (c) a 2-km buffer zone around wetland areas, and (d) malaria risk map showing populated areas that fall within the buffer zone around wetlands.

polarimetric remote sensing. High spatial resolution data will allow for small-scale regional analysis of vector breeding sites, as the new ultrafine mode will provide 3-m spatial resolution data, covering a swath of 25 km in a singular polarization. In theory, the selective look direction option will increase imaging revisit time and allow for increased temporal resolution to better provide near-real-time imagery for monitoring disease outbreak situations. Polarimetric data will provide increased information content useful for improved land cover classifications with single-date imagery (McNairn, 2001) and information on water conditions within a wetland environment (Sokol, 2001).

RADARSAT-2 will offer the highest resolution commercial SAR data available to the remote sensing community, with 3-m spatial resolution capability. One of the main limiting factors in the use of SAR for many applications has been related to insufficient spatial resolution to identify important environmental targets. In the application of remotely sensed imagery for assessing environmental indicators of disease, identifying localized targets is critical to obtain a realistic result of the potential presence of vector breeding grounds. In the case of malaria, small pools of water often found in areas of particularly low standards of living and poor sanitation can be prime locations for vector breeding. Seasonal ponding associated with extreme weather conditions (e.g., El Niño – La Niña) are also important vector breeding grounds, and often very localized. With this, the current resolution provided by RADARSAT-1 is the primary limiting factor in the operational development of this application. RADARSAT-2 will provide the potential to identify these areas with ultrafine mode imagery.

Another critical requirement of disease surveillance from space is timely data capture and delivery. Currently, RADARSAT-1 offers near-real-time data delivery, with a revisit period of approximately 1–3 days at high latitudes and an average of 3–5 days closer to the equator. It is expected that the revisit periods for RADARSAT-2 will be significantly greater, particularly if the manoeuvre between right- and left-looking mode is made operational (Lukowski et al., 2002). A preliminary assessment on standard beam only, using the RADARSAT swath planning application (SPA), indicates that RADARSAT-2 will be capable of a revisit imaging period in tropical areas near the equator of approximately 1–2 days if all possible imaging opportunities are taken advantage of. For the application being discussed, shallow beam modes are preferable, which may limit this increase in temporal resolution, although the need for time-critical information as disease outbreaks and epidemic situations arise will be better served with RADARSAT-2 than with RADARSAT-1.

One of the main advancements with RADARSAT-2 will be its capability for multiple and fully polarimetric imaging. Although the scientific community has had limited opportunities to explore the operational possibilities of space-borne polarimetry, several studies using airborne multipolarized SAR have concluded that higher classification accuracy can be obtained, as compared with that using single linearly polarized data (Foody et al., 1994; Lee et al., 1994; Schmullius and Evans, 1997; Boerner et al., 1998; Pope et al., 1992). Although C-HH polarization can be used to monitor wetland environments where vector breeding is likely to occur, increased information content with polarimetric data will likely facilitate more accurate land cover mapping (Ambrosia et al., 1989; Linthicum et al., 1991; Crevier and Pultz, 1996b).

The breeding habitats of many vector-borne diseases can be very specific and may require a detailed classification to identify individual habitats (Pope et al., 1993). For instance, within the broad class of wetlands, it would be useful to identify different wetland types like swamps, marshes, and peatlands, since certain wetlands have more available standing water for mosquito breeding. The potential also exists to classify wetland types with polarimetric data, as will be available with RADARSAT-2. Researchers at the CCRS have used airborne polarimetric C-band SAR data to investigate wetland types along the shores of the St. Lawrence River in Ontario, Canada. Sokol et al. (1998) identified five different wetland types using a number of polarimetric parameters (polarimetric plots, linear co- and cross-polarizations, pedestal height, and polarization ratios). The polarimetric data enabled a broad class discrimination of wetland vegetation. Differences in vegetation density, related to wetland type, were reflected in the linear polarized backscatter values, and the polarization signatures gave some indication of differences in vegetation structure. Using shallow incidence angles (greater than 50°), the polarization responses indicated beam interaction with the vegetation, rather than ground or water targets (which would likely be seen using steeper incidence angles). The results demonstrate the ability of polarimetric radar to discriminate wetland classes and offer insight into the potential capabilities of RADARSAT-2.

Conclusions

Remote sensing operational applications ultilizing earth observation satellite data are increasingly being developed, including applications relating to disease monitoring. For decades, research has been carried out in this field using optical data from sensors such as Landsat, with results consistently challenged by frequent cloud cover that often persists in tropical areas where vector-borne diseases are most common. Although little research has been done on the use of space-borne radar imagery for disease risk mapping, results presented here demonstrate the potential for RADARSAT-1 to identify environmental variables (wetland characteristics) conducive to the breeding of malaria-carrying *Anopheles* mosquitoes. The all-weather capability of SAR and the sensitivity of SAR to surface moisture conditions and target geometry are identified as the primary advantages of radar remote sensing for this application.

It is anticipated that RADARSAT-2 will provide increased potential for this application, particularly with high spatial and temporal resolution data and polarimetric capabilities. The ultrafine mode of RADARSAT-2 will likely facilitate the identification of small areas that are associated with disease risk. Outbreak situations may be targeted and monitored on a timely basis with the increased imaging schedule that will be available with left- and right-looking operations. Lastly, polarimetry will contribute to current research that indicates the potential for increased classification accuracy and more detailed classification. With four linear polarizations and fully polarimetric parameters available with RADARSAT-2, information can be derived on vegetation structure and water conditions. This will contribute to the operability of radar imagery for disease monitoring in terms of accurately identifying potential areas at risk of vector-borne disease.

Acknowledgements

The authors wish to acknowledge the valuable contributions of Dr. John Beier of Tulane University, Dr. Charles Mbogo of the Kenya Medical Research Institute (KERMI), and Dr. Emmanuel Mushinzimana of the International Centre for Insect Physiology and Ecology (ICIPE). Gratitude is also extended to Willy Bruce and Dr. Heather McNairn of the CCRS for their editorial contributions to this paper.

References

Ambrosia, V.G., Linthicum, K.G., Bailey, C.L., and Sebesta, P.D. 1989. Modelling Rift Valley Fever (RVF) disease vector habitats using active and passive remote sensing systems. In *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, IGARSS '89*, 10–14 July 1989, Vancouver, B.C. IEEE, New York.

Arzandeh, S., and Wang, J. 2002. Texture evaluation of RADARSAT imagery for wetland mapping. *Canadian Journal of Remote Sensing*, Vol. 28, No. 5, pp. 653–666.

Beck, L.R., Rodríguez, M.H., Dister, S.W., Rodríguez, A.D., Rejmánková, E., Ulloa, A., Meza, R.A., Roberts, D.R., Paris, J.F., Spanner, M.A., Washino, R.K., Hacker, C., and Legters, L.J. 1994. Remote sensing as a landscape epidemiologic tool to identify villages at high risk for malaria transmission. *American Journal of Tropical Medicine and Hygiene*, Vol. 51, pp. 271–280.

Beck, L.R., Rodríguez, M.H., Dister, S.W., Rodríguez, A.D., Washino, R.K., Roberts, D.R., and Spanner, M.A. 1997. Assessment of a remote sensing based model for predicting malaria transmission risk in villages of Chiapas, Mexico. *American Journal of Tropical Medicine and Hygiene*, Vol. 56, No. 1, pp. 99–106.

Boerner, W.M., Mott, H., Luneburg, E., Livingstone, C., Brisco, B., Brown, R.J., and Patterson, J.S. 1998. Polarimetry in radar remote sensing: basic and applied concepts. In *Manual of remote sensing, Vol. 2, Principles and applications of imaging radar.* Edited by F.M. Henderson and A.J. Lewis. John Wiley and Sons, Inc., New York. pp. 271–357.

Costa, M.P. de F., Novo, E.M.L. de M., Mitsu, F., II, Ballester, M.V., and Ahern, F. 1997. Classification of floodplain habitats (Logo Grande, Brazilian Amazon) with RADARSAT and JERS-1 data. In *Proceedings of Geomatics in the Era of RADARSAT, GER'97*, 25–30 May 1997, Ottawa, Ont.

Crevier, Y., and Pultz, T.J. 1996a. Analysis of C-band SIR-C radar backscatter over a flooded environment, Red River, Manitoba. In *Proceedings of the 3rd International Workshop on Applications of Remote Sensing in Hydrology*, 16–18 Oct. 1996, Greenbelt, Md. pp. 47–60.

Crevier, Y., and Pultz, T.J. 1996b. Analysis of C-band SIR-C/X SAR radar backscatter over a flooded environment, Red River, Manitoba. In *Proceedings of the 3rd International Symposium on Applications of Remote Sensing in Hydrology*, 16–18 Oct. 1996, Greenbelt, Md. pp. 47–60.

Foody, G.M., McCulloch, M.B., and Yates, W.B. 1994. Crop classification from C-band polarimetric radar data. *International Journal of Remote Sensing*, Vol. 15, No. 14, pp. 2871–2885.

Hay, S.I. 2000. An overview of remote sensing and geodesy for epidemiology and public health applications. *Advances in Parasitology*, Vol. 47, pp. 1–35.

Hay, S.I., Snow, R.W., and Rogers, D.J. 1998. From predicting mosquito habitat to malaria seasons using remotely sensed data: practice, problems and perspectives. *Parasitology Today*, Vol. 14, No. 8, pp. 306–313.

Hayes, R.O., Maxwell, E.L., Mitchell, C.J., and Woodzick, T.L. 1985. Detection, identification, and classification of mosquito larval habitats using remote sensing scanners in earth-orbiting satellites. *World Health Organization Bulletin*, Vol. 63, pp. 361–374.

Hugh-Jones, M. 1989. Applications of remote sensing to the identification of the habitats of parasites and disease vectors. *Parasitology Today*, Vol. 5, pp. 244–251.

Jovanovic, P. 1987. Remote sensing of environmental factors affecting health. *Advanced Space Research*, Vol. 7, pp. 11–18.

King, P.E. 1979. Problems of spatial analysis in geographical epidemiology. *Social Science & Medicine Part D Medical Geography*, Vol. 13, pp. 249–252.

Lee, J.-S., Grunes, M.R., and Kwok, R. 1994. Classification of multi-look polarimetric SAR imagery based on complex Wishart distribution. *International Journal of Remote Sensing*, Vol. 15, No. 11, pp. 2299–2311.

Linthicum, K.J., Bailey, C.L., Angleberger, D.R., Cannon, T., Logan, T.M., Gibbs, P.H., Tucker, C.J., and Nickeson, J. 1991. Towards real-time prediction of Rift Valley Fever epidemics in Africa. *Preventative Veterinary Medicine*, Vol. 11, pp. 325–334.

Lukowski, T.I., Khellah, F., Charbonneau, F.J., and Yue, B. 2002. Synthetic aperture radar for search and rescue: evaluation of advanced capabilities in preparation for RADARSAT-2. In *Proceedings of the SPIE Conference on Automatic Target Recognition XII*, 2–4 April 2002, Orlando, Fla. Edited by F.A. Sadjadi. Proceedings of SPIE, Vol. 4726.

McNairn, H. 2001. Agriculture. In *Applications potential of RADARSAT-2*. Edited by J.J. van der Sanden and S.G. Ross. Canada Centre for Remote Sensing, Ottawa, Ont.

PCI Geomatics Enterprises Inc. 2001. *PCI software user manual, version 7.0.* PCI Geomatics Enterprises Inc., Richmond, B.C.

Pope, K.O., Sheffner, E.J., Linthicum, K.J., Bailey, C.L., Logan, T.M., Kasischke, E.S., Birney, K., Njogu, A.R., and Roberts, C.R. 1992. Identification of central Kenyan Rift Valley Fever virus vector habitats with Landsat TM and evaluation of their flooding status with airborne imaging radar. *Remote Sensing of Environment*, Vol. 40, pp. 185–196.

Pope, K.O., Rejmánková, E., Savage, H.M., Arredondo-Jimenez, J.I., Rodríguez, M.H., and Roberts, D.R. 1993. Remote sensing of tropical wetlands for malaria control in Chiapas, Mexico. *Ecological Applications*, Vol. 4, No. 1, pp. 81–90.

Pope, K.O., Rejmankova, E., Paris, J.F., and Woodruff, R. 1997. Detecting seasonal flooding cycles in marshes of the Yucatan Peninsula with SIR-C polarimetric radar imagery. *Remote Sensing of Environment*, Vol. 59, pp. 157–166.

Ramsey, E.W., III. 1995. Monitoring flooding in coastal wetlands by using radar imagery and ground-based measurements. *International Journal of Remote Sensing*, Vol. 16, No. 13, pp. 2495–2502.

Schmullius, C.C., and Evans, D.L. 1997. Synthetic aperture radar (SAR) frequency and polarization requirements for applications in ecology, geology, hydrology, and oceanography: a tabular status quo after SIR-C/X-SAR. *International Journal of Remote Sensing*, Vol. 18, No. 13, pp. 2713–2722.

Sokol, J. 2001. Hydrology. In *Applications potential of RADARSAT-2*. Edited by J.J. van der Sanden and S.G. Ross. Canada Centre for Remote Sensing, Ottawa, Ont.

Sokol, J., McNairn, H., Pultz, T.J., Touzi, R., and Livingstone, C. 1998. Monitoring wetland hydrology with airborne polarimetric radar. In *Proceedings of the 20th Annual Canadian Remote Sensing Symposium*, 10–13 May 1998, Calgary, Alta. Canadian Aeronautics and Space Institute, Ottawa, Ont. pp. 111–114.

Thomson, M.C., Connor, S.J., Milligan, P.J.M., and Flasse, S.P. 1997. Mapping malaria risk in Africa: What can satellite data contribute? *Parasitology Today*, Vol. 13, No. 8, pp. 313–318.

Wagner, V.E., Hill-Rowley, R., Narlock, S.A., and Newson, H.D. 1979. Remote sensing: a rapid and accurate method of data acquisition for a newly formed mosquito control district. *Mosquito News*, Vol. 39, pp. 282–287.

Washino, R.K., and Wood, B.L. 1993. Application of remote sensing to vector arthropod surveillance and control. *American Journal of Tropical Medicine and Hygiene*, Vol. 50, pp. 134–144.

Woodzick, T.L., and Maxwell, E.L. 1977. Multidate mapping of mosquito habitat. In *Proceedings of the 11th International Symposium on Remote Sensing and the Environment*, Ann Arbor, Mich.

World Health Organization. 1998. Malaria. World Health Organization Fact Sheet 94. Available from http://www.who.int/inf-fs/en/fact094.html.