RADARSAT-1 for Monitoring Vector-borne Diseases in Tropical Environments: A Review

S.G. Ross[1], M.C. Thomson[2], T.Pultz[1]

[1]Canada Centre for Remote Sensing
Natural Resources Canada
588 Booth Street
Ottawa, ON. K1A 0Y7
Ph. (613) 9471271 Fx. (613) 947-1385
Shannon.Ross@ccrs.nrcan.gc.ca

[2] MALSAT Research Group
School of Tropical Medicine
Pembroke Place, Liverpool L3 5QA UK
Ph. (0)151 708 9393
mthomson@liv.ac.uk

Abstract

The incidence and spread of vector-borne infectious disease is an increasing concern in many parts of the world, especially tropical areas. Earth observation techniques are becoming a recognised means of monitoring and mapping disease risk, and have proven useful in associating environmental indicators with various disease and their vectors. Geographically, the areas that bare the burden of infectious disease are often remote and not easily monitored using traditional, labour intensive survey techniques. High spatial and temporal coverage provided by spaceborne sensors allows for the investigation of large areas in a timely manner. Since the majority of infectious diseases occur in topical areas, however, one of the main barriers to earth observation techniques is high cloud-cover. Synthetic Aperture Radar (SAR) technology offers a solution to this problem by providing all-weather, day and night imaging capability. RADARSAT-1, Canada's first Earth observation satellite is being used operationally for many applications, including flood monitoring, land cover mapping and disaster management. This paper will discuss several SAR remote-sensing applications and consider the potential of RADARSAT-1 for disease monitoring applications.

Introduction

The 21st century is experiencing rapid advancement in space-related technologies, with increased attention and investment in satellite applications such as telecommunications and Earth observation. At the same time, in poor countries, especially in the tropics, changing environments, breakdown in control efforts and drug resistance are being associated with the re-emergence of certain communicable diseases. In particular, vector-borne diseases such as malaria are plaguing the African continent, where limited economic and social development is already strained. Space-related technological advancements have the potential of providing effective tools that can be used to improve disease surveillance and control from a local, regional to global scale.

Environmental variables such as rainfall, temperature, humidity, vegetation status, soil moisture and land cover can be used to create risk maps indicating areas where vector populations may be abundant or human-vector contact may occur. Furthermore, where data is available frequently for the same area and in near-real time, such variables may be used to monitor changes in the environment, which may in turn predict changes in disease incidence and perhaps even predict epidemics. Traditionally, labour intensive survey techniques were used to study such environmental processes; however, recent advances in the field of geomatics have proven highly useful in collecting this data. Remote sensing and geographic information systems (GIS) have the capability of storing, manipulating, and retrieving large amounts of spatial data, and can be effective decision-making aids to health officials, governments and research scientists around the world. In recent years, there has been a great deal of interest in geomatics, which incorporates the technologies of remote sensing and GIS. Many scientists have noted the potential of geomatics in understanding temporal and spatial patterns of vector-borne diseases, as well as monitoring and mapping potential risk to human populations (Wood *et al.*, 1991; Washino *et al.*, 1993; Connor *et al.*, 1997; Hay *et al.*, 1998, 2000; Thomson and Connor, 2000).

There is little doubt that remote sensing and GIS have the potential to be efficient and effective tools in the fight against the world's emerging infectious diseases. Most researchers in the field support this vision, but many also recognise the limitations associated with the technology to date. Low spatial/high temporal resolution data on rainfall and vegetation status from Meteosat and NOAA- AVHRR are widely used by food security organizations in Africa and are currently being promoted for routine use in malaria early warning systems (WHO, 2001). High spatial/low temporal resolution data from Landsat has been widely applied to landscape epidemiology studies of insect vectors of disease (Beck *et al.*, 2000). One of the most common technical limitations to both these approaches is cloud-cover seen in optical data (Wood *et al.*, 1991; Washino *et al.*, 1993; Thomson *et al.*, 1997).

Given that most of the diseases of interest (e.g. malaria, filariasis, dengue, etc.) in question are prevalent in tropical areas, with high temporal and spatial cloud-cover conditions, it is often difficult to acquire useful cloud free data in a timely manner. The focus of our research will address this limitation by considering the potential use of Synthetic Aperture Radar (SAR) technology for disease monitoring. Following similar methodologies to those published using optical data, the authors will consider how RADARSAT-1 data may fill some of the gaps found in the current applications of remote sensing for disease monitoring, and specify what additional and complimentary information SAR may provide.

RADARSAT-1

Launched in November 1995, RADARSAT-1 is a Canadian initiative involving the Canadian government, the United States, and private industry. The RADARSAT-1 spacecraft carries a C-band Synthetic Aperture Radar (SAR) sensor that transmits and receives horizontally polarised (HH) microwave signals to image the Earth both day and night, since it generates its own energy independent of the sun. In addition, the chosen frequency of RADARSAT-1 can penetrate clouds and haze, increasing the useful geographic and temporal coverage significantly over optical sensors. The main application of RADARSAT-1 is sea ice monitoring in arctic regions, however the technology has been proven useful for monitoring many of the Earth's resources and environmental changes. In particular, land applications related to hydrology, agriculture, and land use mapping have benefited from the capabilities of RADARSAT-1 to provide reliable SAR imagery.

RADARSAT-1 has the unique ability to steer its variable mode radar beam over a wide area. The flexible swath width (50-500km), spatial resolution (8-100 metres), and incidence angle (10-60 degrees) provides users with many data options which can be suited to a variety of applications. When selecting remotely sensed data, users must consider the trade-off between spatial coverage and spatial resolution. RADARSAT's wide area swaths provide excellent regional coverage (up to 500 km.) with a coarse spatial resolution, while detailed studies may be carried out using fine resolution data with swath coverage of 50 km. The specifications of the RADARSAT-1 SAR are provided in table 1.

Centre frequency	5.3 GHz (C-band)
Bandwidth	11.6, 17.3 or 30 Mhz
Polarisation	HH
Spatial resolution	9-100 m
Swath width	50-500 km
Incidence angle	10º- 58º

Table 1: SAR sensor characteristics for RADARSAT-1

RADARSAT-1 operates in a sun-synchronous polar orbit, providing complete global coverage on a regular and timely basis. The ground track of the satellite is repeated every 24 days, however the steerable beam capability and wide swath coverage allows for most regions on the Earth to be imaged more frequently. High latitudes (north of 70°) may be imaged on a daily basis, as is done in the Canadian Arctic regions, while areas closer to the equator can achieve repeat coverage every 3-6 days. Orbit specifications for RADARSAT-1 are presented in table 2. Operating beam mode specifications are provided in table 3.

Altitude (average)	798 km
Inclination	98.6 degrees
Period	100.7 minutes
Sun-synchronous	14 orbits per day
Repeat cycle	24 days

Table 2: Orbit characteristics for RADARSAT-1

Mode	Approximate Incidence Angle [degrees]	Approximate Swath Width [km]	Approximate Resolution: [1] Rg x Az [m]	Approximate Looks [2] [Rg x Az]
Standard	20-49	100	25 x 28	1 x 4
Wide	20-39	150	25 x 28	1 x 4
Extended Low	10-23	170	40 x 28	1 x 4
Extended High	50-60	75	20 x 28	1 x 4
Fine	37-48	50	10 x 9	1 x 1
ScanSAR Wide	20-49	500	100 x 100	4 x 2
ScanSAR Narrow	20-40	300	50 x 50	2 x 2

[1] Ground resolution varies in range, [2] Range and processor dependent

Table 3: Characteristics of RADARSAT-1 operating beam modes

There are several receiving stations for RADARSAT-1 around the world. The satellite can acquire up to 32 minutes of data per orbit, which are either down-linked in real time using 2 simultaneous x-band channels, or stored on one of two onboard recorders until the spacecraft is within range of a ground receiving station. RADARSAT-1's processing facilities cater to many customer's need for timely data, by providing imagery to users within four hours of acquisition when necessary. This service has been particularly useful in operational disaster management and real-time ice reconnaissance operations.

SAR Applications

In assessing the potential of SAR remote sensing for monitoring a given environment, it is important to understand the scattering mechanisms and variables that contribute to the radar backscatter from a target. There are several sensor and target characteristics that will influence radar backscatter, including look direction, image geometry, inherent distortions, speckle noise, number of looks, and environmental conditions. Two of the main target characteristics influencing radar backscatter are target roughness and dielectric properties.

Surface roughness of a target directly relates to the tone and texture of an image signature. For small-scale roughness, diffuse reflectance increases as the roughness increases, resulting in increasingly intense returns to the radar sensor. Larger-scale roughness patterns relate to image texture (spatial distribution of tones), and macro-scale roughness is a function of the overall topography in a given scene. For all these features, wavelength, frequency and incidence angle are determining factors in what is detected as "rough" or "smooth". In general, the strength of the returned signal results from increased scattering as the roughness of a target increases (Lewis *et al.*, 1998).

SAR is also particularly sensitive to the dielectric properties of a target. For most dry surfaces, the dielectric constant ranges from 3 to 8, indicative of low moisture content. Water has a dielectric constant of about 80 (Lewis *et al.*, 1998). Thus, increased moisture content in a vegetative surface results in an increased dielectric constant, and increased radar backscatter. Again, frequency and wavelength characteristics have an influence on the dielectric constant, with longer wavelengths generally providing greater depth of surface penetration and increased volume interaction with the target.

It is beyond the scope of this paper to discuss all the applications of SAR remote sensing, and RADARSAT-1 in particular, however some of the more successful applications will be mentioned for the purpose of demonstrating RADARSAT-1's capabilities as they may relate to disease monitoring.

RADARSAT-1 is an effective tool for mapping land cover in rugged or flat terrain as variable swath widths and resolutions allow for mapping at a variety of scales. The repeat coverage and 'all-weather capability' allows for frequent map updating in areas where cloud cover has so far limited the usefulness of other imaging sensors. Stereo digital elevation model (DEM) extraction from RADARSAT-1 image pairs can provide three-dimensional viewing which can be useful in rugged or high relief areas in terms of mapping erosion patterns and geomorphology. Accurate DEMs are very valuable in epidemiological studies of vector-borne diseases because of the strong association of temperature to altitude. Temperature plays a key role in determining the rate at which parasite and insect development occurs and often accounts for the altitudinal limit on the transmission of vector-borne diseases.

Based on SAR reflectance from certain target geometry, urban land use mapping has become another productive application of RADARSAT-1. Mapping land use change patterns and locations of populated areas is feasible with SAR data. Detailed mapping of urban sprawl and particularly peri-urban areas that interface between urban and rural areas may provide valuable insights into the distribution of malaria in African cities.

Agriculture monitoring from RADARSAT-1 has allowed general crop type characteristics to be assessed on a timely basis. Image analysis of SAR data can provide insight as to local farming practises and management techniques, and can provide input into crop yield models. Soil characteristics such as moisture content and roughness can be mapped and related to crop conditions, erosion identification and irrigation patterns. Since many vector borne diseases are associated with these land cover variables, agricultural monitoring can be important when mapping potential vector breeding habitats.

Of particular significance to disease monitoring is RADARSAT-1's potential for mapping rice crops. Due to the flooded nature of many rice paddies, high radar backscatter results as a function of high corner reflection from the vegetation and flooded surface below (Ross *et al.*, 1998). This target characteristic allows for SAR to be used for mapping and monitoring rice crop acreage. Often disease carrying vectors find suitable breeding grounds in irrigated rice fields (Wood *et al.*, 1991), thus SAR could serve as a useful tool for monitoring such ecological elements which could be related to high vector abundance.

Based on the above-mentioned sensitivity of SAR to target moisture conditions, RADARSAT-1 has been useful for hydrology applications. Operational monitoring of floods on a near-real time basis allows for effective disaster monitoring and management of resources. For instance RADARSAT-1 imagery of the floods in Mozambique in 1999 provided malaria control staff with a clear indication of the scale and distribution of the affected areas. Flood extent and damage mapping, impact assessment and flow predictions can be extracted from SAR images. Similar to agriculture targets, wetland and hydrological parameters may be important indicators of several disease vector-breeding sites.

It has been accepted that HH polarization data provides the best information for detecting flooded areas since small features on the water surface have a smaller influence at HH radar backscatter (Ambrosia *et al.*, 1989; Linthicum *et al.*, 1991). VV polarization data can be strongly effected by small-scale roughness on water targets, and thus result in less separability from non-flooded surfaces (Crevier *et al.*, 1996). C-HH imagery has been found to provide the highest contrast between land and water targets, and thus be readily use to discriminate flooded areas from non-flooded areas (Pultz *et al.*, 1991; Crevier *et al.*, 1996). Longer wavelengths, such as L-band can penetrate farther into a vegetation canopy, and readily identify flooded areas below. However, C-band has also been found to be capable of this, especially with deciduous forest canopies where the dominant scattering source is from the corner reflection mechanism between the tree trunk and standing water.

With further respect to mapping land cover and land use changes, microwave target interactions based on target and imaging geometry allow for valuable image data collection on the Earth's forests. Deforestation can be mapped, as well as useful environmental impact assessment and re-growth evaluation practises. As many disease vectors find new breeding grounds as land use patterns change, this application of RADARSAT-1 data could be particularly useful.

SAR and Disease Monitoring

To date, there have been few published results on the applicability of SAR imagery specifically for disease monitoring, particularly using the recent spaceborne SAR sensors. Pope (1992) considered the use of a high-resolution airborne three-band polarimetric radar system (ERIM / NADC P-3 SAR) for the identification of central Kenyan Rift Valley Fever virus vector habitats.

This work concluded that airborne SAR imagery is useful for detecting flooded areas that can be related to active vector breeding sites of the Kenyan Rift Valley Fever virus. In particular, Pope notes the advantage SAR's 'all-weather capability' and sensitivity to moisture as major advantages.

Several concerns relating to the use of SAR remote sensing appear to be limiting its broader use in the field of disease monitoring. Hay (2000) cites these limitations as 1) difficulty of image interpretation and information extraction due to the complexity of SAR imagery, 2) lack of well calibrated SAR data, 3) lack of adequate software to handle SAR data, and 4) topography problems unique to SAR images, such as inherent image speckle. These are valid concerns based on historical use of SAR data, which has for the most part been airborne. Because radar remote sensing operates in the microwave portion of the electromagnetic spectrum, it is not intuitive for the human eye to interpret, as is the case with optical imagery. For this reason, interpretation of SAR data is more complex and requires a skilled user for effective information extraction. In recent years however, especially with spaceborne SAR's like ERS and RADARSAT, data are being provided as detected, well-calibrated products that are increasingly straightforward to process, interpret and analyse. Commercial image processing software packages are being developed to deal with unique SAR characteristics, such as speckle interference and topographic effects; however, many of these packages require significantly more effort to facilitate accurate analysis, ease of use and automation of routines. Although it is recognised that radar data has limitations relating to its inherent complexity, the availability of data from recent sensors such as RADARSAT-1 should facilitate increased use of SAR data for appropriate applications such as disease monitoring.

Some of the hypothesised advantages of spaceborne SAR imaging to disease monitoring are the capability for long-term monitoring, regional coverage, and near-real time capabilities. The high-cost and logistical difficulties associated with airborne remote sensing could be reduced with spaceborne monitoring. Although the use of high-resolution imagery (often available with airborne SAR systems) is important for detecting small area vector breeding grounds, lower resolution (20-30m) spaceborne SAR's can be useful for large area monitoring. Over the past decade, there has been a clear need for cost-effective, timely, high-resolution spaceborne SAR systems. RADARSAT-1, as well as other spaceborne SAR platforms (ERS, ALMAZ, ENVISAT) are meeting these challenges.

The methodology of using SAR data for disease monitoring is similar to that which has been used with optical remote sensing in recent years. With well-calibrated, multi-temporal RADARSAT-1 imagery, a geo-referenced, co-registered dataset may be used for image classification. Advanced intelligence-based classification routines such as fuzzy logic based algorithms are most suitable for SAR data, since an assumption of normal data distribution can pose a problem with common routines such as parameterised supervised classifications. The availability and usability of advanced classification algorithms is increasing with the development of several object-oriented software packages which are designed to contend with some of the inherent challenges of SAR data.

Based on SAR's sensitivity to surface moisture conditions, ecological variables relating to vector breeding grounds may be readily identified with a classified SAR image. The land cover parcels associated with the disease vector under investigation may then be correlated with ground data of vector abundance. With this, areas of high vector abundance are tagged as high to low risk, depending on proximity to areas populated by the vectors host (e.g. human hosts for malaria carrying mosquito vectors). The use of Geographic Information Systems (GIS) for cluster analysis and buffer zone generation around host areas can serve as a tool to produce disease risk maps.

In a study to determine the spatial distribution of the parasitic worm, *loa loa* in West and Central Africa, GIS and remote sensing technologies have been used to model the presence/absence of infection in individuals to environmental variables. Initial results suggest that land/forest cover (derived from NOAA-AVHRR satellite data) and soil type (from the FAO digitised soil map of Africa) are significant predictors and a preliminary risk map has been produced (Thomson *et al*., 2000). Testing this model in Cameroon using extensive prevalence survey data has revealed that the satellite data upon which it is based has insufficient spatial resolution to pick out gallery forests in savanna areas where the flies (*Chrysops* spp.) which transmit this disease may be found.

The proposed solution to this problem of low spatial resolution hinges on the recent availability of large radar mosaics acquired over the tropical regions by the SAR instruments on board the ESA ERS and the NASDA JERS-1 spacecrafts (CAMP - Central Africa Mosaic, and GRFM - Global Rain Forest Mapping - projects). The bio-physical parameters considered in this study are the swamp forest and lowland rain forest structure, and flood extent. The intention is to map these quantities over an entire tropical floodplain; in this case the Congo River wetland in Central Africa, with high spatial resolution (on the order of 100 meters). CAMP is an initiative started in 1994 by the European Commission TREES project, and consists of a blanket coverage of the Central African region at two dates using the ESA ERS C-band radar instruments. GRFM is a project promoted and funded by the Japanese Space Agency NASDA in 1996 and executed through an international cooperative effort, where the European Commission JRC Space Applications Institute, the Jet Propulsion Laboratory, USA, and NASDA, Japan, are acting as main processing nodes. The goal is to produce a blanket radar map of the tropical rain forest ecosystems worldwide using the JERS-1 L-band SAR (De Grandi *et al.*, 2000).

Preliminary investigations using the JERS-1 data suggest that the high spatial resolution of the data is sufficient to pick out characteristic differences in the environment related to the forest type in central, west and north-west Cameroon, including the vector habitat of *loa loa* (Thomson unpublished data).

Discussion and Conclusions

Proposals to use remote sensing for monitoring disease environments were put forth as early as 1977, when Woodzick *et al.* presented a paper entitled "Multi-date Mapping of Mosquito Habitat" at the 11th International Symposium on Remote Sensing of Environment. In this project, Landsat data from three separate dates was used to create a land cover map of a region in the United States. Quite simply, the land cover classification was used as an indicator of potential mosquito-breeding habitats by distinguishing different wetland types. Although this idea was proposed before efficient GIS software was readily available, the methodology for mapping and monitoring disease with remotely sensed data has remained the same for the past two decades.

Today, geomatics technologies are beginning to be used in many parts of the world to monitor vector-borne diseases, map high-risk areas, quantify hazardous zones, and assist in disease policy and planning. In 1985, the National Aeronautics and Space Administration (NASA) established the Global Monitoring and Disease Prediction Program in response to the World Health Organisation's (WHO) plea for an effective tool to cope with the growing concern over malaria infection (Clarke *et al.*, 1996). It was hoped that geomatics technology could be used to build a model to predict and control malaria outbreaks by detecting and monitoring the environmental factors that affect patterns of disease risk and transmission. Since then, several collaborations between universities and government agencies have endeavoured to develop effective tools using remote sensing and GIS. For the most part, optical spaceborne sensors, such as Landsat and SPOT have provided data for these studies. The timeliness and cost-effectiveness of spaceborne platforms has met the needs of monitoring disease outbreaks all over the world and at a variety of scales. However, low spatial resolution (less than 20m) sensors have been limiting for small scale mapping and detecting local vector breeding sites. Furthermore, frequent cloud-cover found the tropical disease ridden areas has restricted the accessibility to useful imagery from optical sensors.

The most recent generation of spaceborne SAR systems, such as RADARSAT-1, address some of these challenges by providing all weather, day and night imaging at a resolution as high as 9 metres. RADARSAT-1's selectable beam modes allow for user specified configurations to meet the needs of a given region or application. Orbit characteristics allow for near-real time data processing, which meets the requirement for rapid environmental assessment to facilitate early action and mitigation of disease impacts(Ambrosia *et al.*, 1989; Hay, 1997).

Many sensors have proven useful for disease monitoring in cloud-free conditions. SAR has great potential for imaging at high spatial and temporal resolutions during periods of persistent cloud cover. But perhaps the most useful tool for monitoring and mapping vector borne disease will be discovered with the integration of both optical and SAR datasets. Land cover classification accuracy calculated with combined radar, visible-NIR bands has been found to be significantly higher than with radar or visible-NIR bands alone, particularly using advanced classification routines such as neural networks (Augusteijn *et al.*, 1998) or fuzzy logic based algorithms. Further to this, accurate ground truth data will complement remotely sensed data and allow for validation exercises to be conducted. For example, Richie (1993) investigated the value of tide gauge data coupled with remotely sensed rainfall estimations for the surveillance of the black salt marsh mosquito found in coastal environments. It was found that this type of information, analysed in an integrated manner, provided accurate detection of the mosquito habitats. Advanced *in situ* data collection techniques, including the use advanced Global Positioning Systems (GPS) and on-line geospatial databases are allowing for improved ground truth routines.

The successes of RADARSAT-1 will be further developed with the launch of RADARSAT-2 in 2003. RADARSAT-2 will provide all imaging modes of RADARSAT-1, as well as 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 will allow for high-resolution imaging (up to 3 metres), right and left-looking geometry and fully polarimetric remote sensing. The selective look direction option will increase imaging revisit time and allow for increased temporal resolution to better provide near-real time imagery for disease outbreak monitoring. High spatial resolution data will allow for small-scale regional analysis of vector breeding sites. Polarimetric data will provide increased information content useful for improved land cover classifications with single-date imagery. Table 4 outlines the characteristics of each RADARSAT-2 imaging mode.

RADARSAT-2 Imaging Modes	Mode	Approximate Incidence Angle [degrees]	Approximate Swath Width [km]	Approximate Resolution: [3] Rg x Az [m]	Approximate Looks [Rg x Az]
Selective Polarization Transmit H or V Receive H and/or V	Standard	20-49	100	25 x 28	1 x 4
	Wide	20-45	150	25 x 28	1 x 4
	Low Incidence	10-23	170	40 x 28	1 x 4
	High Incidence	50-60	70	20 x 28	1 x 4
	Fine	37-49	50	10 x 9	1 x 1
	ScanSAR Wide	20-49	500	100 x 100	4 x 2
	ScanSAR Narrow	20-46	300	50 x 50	2 x 2
Selective Single Polarization Transmit H or V, Receive H or V	Triple Fine	30-50	50	11 x 9	3 x 1
	Ultra-Fine Wide	30-40	20	3 x 3	1 x 1
	Ultra-Fine Narrow	30-40	10	3 x 3	1 x 1
Polarimetric Transmit H and V on alternate pulses Receive H and V on each pulse	Standard Polarimetric [1]	20-41	25	10.5 [2] or 15.7 [2] x 8.9	1 x 1
	Fine Polarimetric [1]	30-41	25	6 ** x 8.9	1 x 1

[1] *Single-look Complex* [2] *Slant Range* [3] *Ground resolution varies in range*

Table 4: RADARSAT-2 imaging mode specifications

One of the main advancements with RADARSAT-2 will be its capability for multiple and fully polarimetric imaging. Although the scientific community has not had much opportunity to explore the possibilities of space-borne polarimetry, several studies using airborne polarimetric SAR have concluded that classification accuracy is higher as compared to linearly polarized data (Ott *et al.*, 1990; Foody *et al.*, 1994; Lee *et al.*, 1994; Schmullius *et al.*, 1997; Boerner *et al.*, 1998). Although C-band, HH polarization is optimal for monitoring environments where vector breeding is likely to occur (e.g. wetlands), increased information content with polarimetric data will facilitate accurate land cover mapping (Ambrosia *et al.*, 1989; Linthicum *et al.*, 1991; Pultz *et al.*, 1991; Crevier *et al.*, 1996).

Improved techniques of *in situ* measurements and increased availability of advanced operational SAR sensors will provide the tools needed to develop effective analytical techniques for vector borne disease mapping. As scientists begin to exploit the new generation of SAR data sources available, the use of SAR imagery for disease monitoring will be discovered as a viable solution to some of the challenges faced by the field of remote sensing and disease monitoring over the past several decades.

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