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Remote Sensing: Applications in Environmental Monitoring

Mugabo Kalisa G.

Faculty of Engineering Kampala International University Uganda

ABSTRACT

Remote sensing has emerged as a transformative tool for environmental monitoring, offering synoptic, scalable, and near-real-time data essential for managing Earth's dynamic systems. Through satellite-borne, airborne, and terrestrial sensors, remote sensing enables the detection and analysis of geophysical variables such as rainfall, deforestation, freshwater dynamics, sea surface temperature, and biodiversity changes. This paper explores the fundamentals of remote sensing, including sensor types, data acquisition methods, and the electromagnetic spectrum used. It highlights its diverse applications in land use and land cover analysis, water resource management, climate change studies, biodiversity conservation, and disaster risk reduction. Emphasis is also placed on technological advancements, data processing techniques, and the persistent challenges such as calibration errors, algorithm complexity, and sensor design limitations. With ongoing innovations in high-resolution imaging, machine learning, and big data processing, remote sensing stands poised to play an even greater role in guiding sustainable environmental management, particularly in the face of climate change and anthropogenic pressures.

Keywords: Remote Sensing, Environmental Monitoring, Satellite Imagery, Land Use and Land Cover (LULC), Climate Change, Water Resource Management, Biodiversity.

INTRODUCTION

Data from satellites offers great potential for environmental monitoring and resource management, highlighting concerns about accurately detecting geophysical parameters like rainfall, deforestation, freshwater changes, and rising sea surface temperatures (SSTs) related to global warming. Recent advancements allow for measuring subtle sea surface salinity (SSS) changes and their impact on ocean circulation, emphasizing the need for integrating remote sensing with geophysical modeling. Challenges include the creation of high-sensitivity sensors that minimize noise and developing precise retrieval algorithms that reflect complex measurements, often requiring advanced mathematics and validation. Current capabilities are limited to a few parameters, with future advancements focusing on automated data processing and robust algorithms for unexplored parameters. Acquiring ancillary data remains a challenge, and uncertainty in remote sensing often mirrors subjective knowledge uncertainty. Remote sensing uses indirect measurements to infer Earth's surface information via emitted electromagnetic waves, leading to derived observations rather than direct measurements. Potential uncertainty sources include stray radiances, inconsistent methods, and calibration errors, which can affect hydrological applications. However, remote sensing has the potential to improve decision-making across various physical and environmental parameters. It encompasses sensors collecting Earth data across the electromagnetic spectrum, placed on spaceborne, airborne, or terrestrial platforms. Spaceborne sensors on satellites are positioned in geostationary or polar orbits at altitudes between 500 and 10,000 kilometers. Geostationary satellites maintain a fixed position, while polar-orbiting satellites cover the entire Earth in approximately 90 minutes. Satellite sensor types influence observation timing and data collection; low-resolution sensors gather data over large areas in 1-10 km grids, while high-resolution sensors focus on smaller areas. Active sensors like radar and LiDAR emit pulses to illuminate and record reflected radiation, with data volumes rapidly increasing as some sensors observe the same region every five minutes [1, 2].

Fundamentals of Remote Sensing

Remote sensing (RS) is the science of gathering geophysical information about Earth without direct contact with the target. It includes various sensors that collect data about the Earth and its environment through electromagnetic energy reflected, emitted, or transmitted from objects. Different wavelengths and geometries are used to process specific features. Earth observation (EO) satellites provide extensive surface coverage, valuable for studying natural phenomena. Imaging spectrometers or hyperspectral sensors capture spectral information at discrete wavelengths, generating two-dimensional raster images. The RS methodology and its applications include aspects often absent from standard RS discussions, particularly in detecting anthropogenic factors, which present methodological challenges but also new research opportunities. Most RS studies have overlooked anthropogenic factors. RS involves diverse sensors and applications, each type offering varying information and accuracy, operating across different regions of the electromagnetic spectrum (EMS). Passive sensors detect natural radiation from targets, while active sensors generate their energy. Key regions of EMS used include solar remote sensing (visible, near IR, shortwave IR), thermal IR remote sensing, and microwaves. Geophysical data can be obtained from spaceborne or airborne platforms, with satellites covering vast areas and airborne sensors offering flexibility and adaptability for specific needs. RS systems are categorized as broad- or narrow-band based on their spectral response functions, with broad-band systems integrating reflected energy over larger wavelength intervals [3, 4].

Applications in Land Use and Land Cover Monitoring

Understanding land use and land cover (LULC) change is essential in ecosystem management and understanding ecosystem diversity and complexity. Remote Sensing data can enhance the use of modern approaches for Land Use Land Cover monitoring. This paper attempts to quantitatively investigate the interdependencies between different land covers and the spatial and non-spatial environmental factors. The study area is Nisos Elafonisos, a coastal Mediterranean ecosystem. The Sentinel-2 sensor was used to classify LULC in 2022, and the digital elevation model data were obtained from ASTER GDEM. This data was used for supervised classification using the Random Forest algorithm to classify six different land cover classes. Three different sources of environmental data were used to draw different clusters of land cover, altitude, distance to roads, and distance to beaches. All results were merged and tested in a formal testing environment. Automatically selecting and classifying meaningful metrics can represent vegetation patches in geographic space. An automatic tool is developed to select vegetation patches across Brazil, characterizing their vegetation using optical SAR, climatic, and terrain data. Machine learning approaches are used to classify these patches into vegetation classes. This methodology was tested in the Napos region over a major extractive reserve in the Brazilian Amazon, generating an unprecedented map of secondary vegetation and providing evidence of vegetation dynamics over the last few decades. It is essential to monitor LULC composition and changes over time to understand ecosystem condition and functionality. The composition of each land use and land cover class affects ecological processes and economic activities at different levels and should not only rely on location and spatial extent, but also study the land use pattern and the characteristics of each class. The LULC composition of a region is often analyzed using landscape metrics. These metrics quantify the spatial distribution of landscape elements across multiple aspects, including the number, shape, size, and arrangement of land use patches. Change detection analysis based on landscape patterns was studied in many ecosystems on an annual basis and is a widely used method for LULC monitoring. Remote sensing techniques provide a cost-effective and scientifically proven means to develop LULC coverage over large regions of the Earth's surface repeatedly, in a reliable and timely manner. For decades, images from optical remote sensing satellites have been successfully used for LULC monitoring [5, 6].

Applications in Water Resources Management

Remote sensing and GIS have significant potential for studying and managing natural resources by acquiring, storing, analyzing, modeling, and displaying spatial and temporal information, which is vital for decision making. Managing water resources involves various factors such as characterization, availability, economic and social aspects, consumption monitoring, and environmental impact. These technologies complement the limited data from in situ networks with continuous satellite coverage. This paper reviews studies conducted over the last decade in collaboration with the Catalonia water administration, where medium-resolution satellite images were incorporated into daily water resource management to enhance decision-making effectiveness. Remote sensing is beneficial for any environmental resource study as it allows for comprehensive data acquisition, storage, and analysis. Crucially, detecting changes in resource conditions over time is vital for management, especially in evaluating the impacts of human activities. Following a 2002 agreement between Catalonia's water administration and the Universitat Autònoma de Barcelona, efforts began to integrate remote sensing into routine water resource management in Catalonia. The subsequent decade saw successful applications of remote sensing in this complex field, with the paper detailing methodologies applied and challenges faced throughout the studies [7, 8].

Applications in Climate Change Studies

Remote sensing techniques can play an important role in the study of environmental changes at diverse spatial and temporal scales. Thanks to the rapid advances in remote sensing technologies in the past few decades, various sensors have been developed to measure a broad suite of geophysical variables for climate applications. Subsequently, there are numerous opportunities for combining innovations in remote sensing with high-performance computing to advance scientific understanding of the land-atmosphere and ocean-atmosphere interactions. The focus is on studies of climate change and uncertainty using satellite remote sensing data. The applications include observational evidence for trend analyses of temperature and precipitation, land surface temperature change in urban areas, an active microwave for monitoring global wetland, soil moisture assimilation and hydrology forecasting, surface winds and wave prediction in coastal areas, typhoon path prediction, and on a new generation geostationary satellite. To meet the scientific needs of these applications in different domains, a variety of remote sensing data sets from low spaceborne systems to high temporal geostationary systems have been developed and shared for free. In addition to providing remotely sensed data sets, a wide range of infrastructures and cooperative efforts have been established in the international community to advance the applications of remote sensing and promote science and technology transfer and training. Challenges and future development of remote sensing in the field of climate change were also discussed. The climate change studies require accurate observations on a long-term basis, to monitor any variations in space and time on parameters related to the Atmosphere, Oceans, Land surface, and weather-related extreme events. There are satellites in polar orbits capable of viewing all parts of the Earth periodically. These satellites have sensors with much finer spatial resolution than those of meteorological satellites and cover large areas all at once. There are other geostationary satellites with various spectrums to see the Earth continuously. To monitor the soil moisture levels of the ocean globally in a systematic way, a new satellite is to be planned [9, 10].

Biodiversity and Habitat Monitoring

Remote sensing can help detect rare biodiversity events and evaluate conservation effectiveness. Remote sensing can help detect biodiversity events too rare to be assessed with conventional methods. It reveals biodiversity through broad changes in the landscape associated with ecological processes such as species extinction, invasive species encroachment, or landscape fragmentation. These applications provide a good balance of the tangible benefits of remote sensing with an established and tested theory in the field of ecology. The emphasis is placed on well-defined conceptual models that focus on research objectives and determine candidate pre-conditions before testing with remote sensing. In situations where the landscape or processes of interest are changing rapidly and understood well, as in some of the case studies presented, remote sensing can provide near real-time hazard detection that can arm conservationists with evidence to prompt speedy action. The ability to assess positive cases of conservation effectiveness was also noted at this workshop. Monitoring systems have been established where remote sensing plays a crucial role, primarily focusing on fire management effectiveness, but the benefits of detecting positive trends using remote sensing have yet to be fully realized due to complex social and institutional factors. There was, however, an explicit call for more work on the positive case detection of conservation effectiveness, particularly regarding remote sensing. Satellite data are accumulating at such a rapid pace that it is becoming feasible to track changes in broad vegetation types and forest cover for much of the Earth's surface. Emerging tools that make these datasets accessible to non-remote sensing experts were considered highly needed for on-the-ground conservationists in developing nations to harness the potential value of this information [11, 12].

Disaster Management and Risk Assessment

Natural and manmade disasters have significant impacts on social, economic, and environmental development, affecting the quality of life for many. The role of remote sensing (RS) in disaster management is examined through three key studies. The first highlights a landslide inventory map for St Lucia, an island prone to landslides from intense rainfall. The second discusses tsunami damage along Japan's Sendai coast following the catastrophic March 11, 2011, event. The third involves landslide characterization in Papanice, Southern Italy, using satellite data to assess slope geometry and surface roughness. Advances in satellite technology enhance remote sensing's effectiveness in disaster management by providing rapid assessments. Innovations in technology facilitate better quantification of the social and economic impacts of disasters, leveraging high-resolution satellite data and global maps of human settlements. Increasingly affordable and efficient navigation and airborne laser scanning sensors have advanced the monitoring of disaster impacts, land cover changes, and environmental conditions, significantly improving response capabilities in disaster management [13, 14].

Technological Advances in Remote Sensing

After over 30 years, the European Space Agency's ERS-1 satellite continues providing unique ocean data despite plans for shutdown. Critical data, like ocean surface wind speed and real-time sea surface temperatures, are still received from the ATSR-1 and 2 systems. Current missions are diverse, with future programs involving interferometers for multiscale missions being pursued by national and multinational agencies. Active satellites such as MODIS, along with quasi-geostationary satellites like GOES, MTSAT, and MSG, enhance operational capabilities. These platforms promise significant data generation at global scales with sub-daily intervals. While current coarse resolution systems are suitable for long-scale monitoring, they lack the accuracy of high-resolution products. Modeling efforts from this data are improving predictions of oceanic and atmospheric features. Current work focuses on generating adjusted input data from low-resolution models for high-resolution predictions on a basin scale. Ensuring compatibility in products and forecasts from both models is essential. Techniques are being developed to create and transmit blended products of various ocean processes and biogeochemical data in real time [15, 16].

Data Processing and Analysis Techniques

The use of remote sensing data necessitates extracting information from readily available images. Most contemporary digital satellite data consists of multispectral recordings of the Earth captured in various spectral bands, making their manipulation distinct from traditional single-band films. This chapter discusses the extent to which standard video-channel display methods can handle these multi-band images. Typically, multi-band satellite data is organized into three multi-channel images by representing successive spectral channels through grayscale levels. There isn't a definitive solution for which three channels to use; however, Earth resources satellites select models covering key invisible radiation channels related to water vapor and chlorophyll absorption. Even with minimal selection discretion, these models improve interpretation quality over non-color-coded multi-channel images. While operators may not know the exact spectral domains, computers can program multi-channel displays to operate unaided. Most satellite images hold discriminatory information about the Earth's surface for visual analysis, with clipped images corrected for background intensity, often termed dark current compensation in digital imaging. Corrected Top of Atmosphere (TOA) or surface reflectance is influenced by solar zenith angles, which vary widely geographically and temporally. Geometric correction relies on the recorded satellite trajectory and terrain elevation databases, addressing positioning discrepancies and warping image files. Calibration aligns satellite sensors with real-world values. The advantage of satellite-based sensor systems lies in their global data coverage, with new observations often arriving before earlier values are processed, affecting data homogenization tasks [17, 18].

Challenges and Limitations of Remote Sensing

As in any other field of engineering, remote sensing challenges exist. Yet it has to be admitted up front that the remote sensor development and environmental monitoring fields are extremely popular and therefore an active realm of research. This does not mean that all events are easy, inexpensive, or straightforward. Several challenges exist in the field. There are many challenges in the design of remote sensors. Perhaps the foremost challenge in remote sensor design stems from Newtonian physics, where sensitivities of optical signatures to surface reflectance or emissivity, material composition, vegetation cover, canopy water content, soil moisture content, or temperature, etc., increase or approach the maximum in the spectral ranges where limited atmospheric windows lie. Therefore, designing sensors in these ranges is always the first challenge. But at the same time, constructing an instrument that has extremely high sensitivity would easily lead to instrument noise that degrades the signal-to-noise ratio. In addition, spectral signatures can be isolated from the surface material composition with broad details, but the other opposing natural variables would take their toll as well: cloud and aerosol constituents, atmospheric profiles, solar zenith angles, surface conditions, and uncertainties, etc. While they can all accurately be measured and mitigated, they all need to be integrated into the retrieval algorithms, which in turn complicates the design of the whole system. There are also scientific challenges. Scientific challenges stem partly from the physical principles that those sensors are designed to sense. A detailed understanding of a complex, nonlinear, and diverse physical measurement process is required for developing a robust retrieval algorithm that describes the process in sufficient mathematical and physical detail while allowing the remotely sensed signals to be inverted with good measure. Improving on measurement second derivatives, fine-grained spectral resolution, higher illumination co-wavelengths, multispectral approaches, or other exotic techniques may help. But they are all software-based methodologies that are beyond those design challenges. However, a prior feasible system design is required as the most logical sidewalk. The future of the remotely sensed data should ideally be in an automated fashion, where very quick, reliable, and usable data processors would rapidly retrieve remotely sensed data with little or no human interference [19, 20].

Case Studies in Environmental Monitoring

Environmental monitoring and change detection with remote sensing: the potential of remote sensing applications in environmental monitoring, a variety of vegetation, bare soil, and water land cover classes may change during time, and with the dynamics of soils and climate. To monitor these changes operationally, various remotely sensed data sources and change detection methods were investigated. The implementation of the change detection in a mapping scenario for products on the local, national, and continental scale was defined. An overview of change detection algorithms as implemented in a software package was presented. A variety of change detection approaches were successfully applied in the mapping scenario with good accuracy for the local scale and fair to moderate accuracy for the. Additionally, the robustness of temperature change monitoring with MODIS LST was investigated. It was shown that after fitting a modulation model to the weekly LST statistics, a perfectly smooth temperature time series can be produced, suitable to detect random or systematic disturbances like abrupt temperature jumps and trend changes. Applications in industrial monitoring were shown, such as the detection of burning mines and older land reclamation actions, and an example of the precaution of burn violations from space. A proof of concept demonstrated that systematic radiometric calibration of time series of GOSAT XCO2 observations is instrumental for long-term monitoring of CO2 emissions from domestic and industrial sources with remote sensing. These case study examples depict the potential of theoretical developments in remote sensing applications and paved the way for specially designed prototype systems for particular applications. Multispectral satellite data has a significant role in environmental studies such as vegetation monitoring, desertification category, urban area mapping, politics and war studies, to previous year alterations, and so on. These data can compute spectral vegetation indices (NDVI, EVI, etc.) and temperature/obsurf for observing various environmental factors such as vegetation density, moisture, temperature of land, earth, ocean surface, and so forth [21, 22].

Future Directions in Remote Sensing Research

Advances in technology and sensor development have enhanced earth observation capabilities, emphasizing the need for context on achievable outcomes with current technologies and future expectations. Coastal systems are complex, integrating land, ocean, atmosphere, and socio-economic factors. Effective management requires a solid understanding of ocean processes and their variations across various temporal and spatial scales. Significant innovation opportunities exist by leveraging new technologies and data sources. While global datasets are produced and archived automatically, analysis costs remain high. Coastal issues like oil spill response, freshwater resource monitoring, and wetland analysis exhibit potential for strong data-driven programs. Advanced algorithms for volume imagery retrieval and sensor data fusion are essential. Additionally, there is a need for automated analysis of complex coastal systems, utilizing hyperspectral sensors and effective methods for large-pixel/frame size sensors in dynamic scenarios. High temporal resolution data from new multiangle sensors combined with bio-optical modeling can assist coastal states in detecting stress in dynamic ecosystems. Creating combined systems for atmospheric observations and in situ networks, along with research into automatic cloud detection algorithms for ocean color correction, is vital for further progress. Remote sensing now also enables very high spatial resolution systems [23, 24].

CONCLUSION

Remote sensing has revolutionized the way we observe and manage Earth's natural and human-influenced environments. Its ability to provide consistent, large-scale, and temporally rich data makes it indispensable for addressing complex environmental challenges. As demonstrated through applications in land cover change detection, water resource evaluation, climate variability monitoring, and biodiversity assessment, remote sensing facilitates data-driven decision-making and proactive environmental stewardship. However, its effectiveness is moderated by limitations in sensor sensitivity, algorithm robustness, and data accuracy. Continued investment in sensor innovation, algorithm development, and interdisciplinary collaboration is critical to overcoming these barriers. Future progress hinges on automated data processing, improved spatial-temporal resolutions, and accessible platforms for non-experts. In sum, remote sensing is not only a scientific asset but a strategic tool for building resilience and sustainability in a rapidly changing world.

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