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RESEARCH ARTICLE

# Survey of Radiometric Techniques for Prediction of Meteorological Phenomena

**Kausik Bhattacharyya**[1], **Manabendra Maiti**[2], **Salil Kumar Biswas**[3], **Judhajit Sanyal**[2]*

**1** Dept. of Physics, Tamralipta Mahavidyalaya, Tamluk, East Medinipur-721636, India
**2** Dept. of Electronics & Communication Engineering, Techno International New Town, Kolkata-700156, West Bengal, India
**3** Dept. of Physics, University of Calcutta, 92 APC Road Kolkata-700009, India

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* **Corresponding author**.

judhajit.sanyal.2019@gmail.com

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## Abstract

**Objectives:** The present work illustrates an extensive review of the field of prediction of meteorological phenomena using radiometric measurements and machine learning with specific focus on rain events and their effects on satellite communication. **Methods:** Multiple types of prediction systems and mechanisms are reviewed, with focus on estimation of atmospheric phenomena using standard statistical models and radiometric measurements, with additional focus on the application of modern machine learning-based techniques for accurate estimate generation. Recent work in the domain has been compared, largely in tabular format, with respect to critical statistics such as correlation coefficient, root mean square error, and computational complexity of the techniques. **Findings:** The systems and mechanisms reviewed allow the identification of opportunities in establishment of novel techniques for prediction of meteorological effects and their influence on parameters such as communication signal attenuation. It is also established through the work that there is lack of a suitably accurate model for prediction of rain attenuation for geographical regions prone to greater variations in weather, such as the tropical regions. Consequently, some of the most recent work in this domain has been analyzed in this paper with a view to determine optimal techniques for different scenarios. **Novelty:** The survey identifies the opportunity to improve upon established models for prediction of rain phenomena and their effects on microwave and millimeter wave communication signal attenuation, as well as surveys modern estimation techniques in detail, with a specific focus on statistical and machine learning based methods which can guarantee greater accuracy with significant variation in the observed parameters such as brightness temperature and rain rate. The work seeks to clearly compare some of the newest techniques in the domain with respect to their efficiency as well as complexity, for practical applications.

**Keywords:** meteorological phenomena; prediction; radiometric measurements; microwave; millimeter wave; brightness temperature; machine learning

## 1 Introduction

The prediction of meteorological phenomena has been a field attracting great research interest for many years, due to the possible ramifications of such events on different communication and tracking systems around the world. Accordingly, researchers have examined meteorological phenomena, especially rain, in terms of their effects on microwave and millimeter wave signals[1]. To meet the growing needs of higher data rates for present day communications and multimedia systems, use of electromagnetic spectrum above 10 GHz in microwave and millimeter wave region is an obvious solution. However, the signals in this frequency range get impaired by rain that causes serious attenuation as well as phase shift, especially in tropical and equatorial countries that are characterized by heavy rainfall[2]. In fact, experiments on short radio paths to calculate the effects of rain on attenuation of microwave signals have been performed in the past, as early as the 1970s. Space diversity for microwave signals in the slant path was investigated at X-band frequencies (11.6 GHz) at around the same time, with significant influence on the modelling of rain-induced attenuation[2]. Path-length correction measurements have also been performed by other researchers for tropospheric signal propagation in presence of rain, using radiometric techniques. Rainfall and atmospheric moisture content have been established by multiple researchers as having significant effect on signal attenuation at microwave frequencies, in turn affecting remote sensing capabilities of microwave[3] [4]. Network arrangements of radiometers and rain gauges have been used to measure spatial rain distribution, with excellent accuracy. Rain and atmospheric moisture have been studied in terms of signal attenuation at microwave frequencies from 11.6 GHz to 22.235 GHz as well as the relationship between temperature and signal attenuation[4]. It is also seen that radiometric and precipitation radar-based methods have been extensively investigated for their potential in prediction of meteorological phenomena and their influence on microwave communication signals[5] [6] [7].

Satellite links are, as expected, significantly affected by atmospheric moisture and associated meteorological events, and, as a consequence, attenuation modelling and estimation for such links have been extensively investigated in the past. Location-specific models, while less general, have also been found to yield sufficiently accurate results in specific geographies with widely varying rainfall characteristics. The accuracies of the extant models are found to be affected for extreme climates with significant variation in weather conditions, which are observed in most tropical and equatorial regions, and certain subtropical regions to a significant extent[7] [8] [9] [10]. The need for novel attenuation models can also be identified from the performance of many of the standard models, such as the ITU-R model, in locations such as Southeast Asian countries[11] [12]. In recent times, a number of researchers have also investigated the performance of different algorithms in predicting rain attenuation[13] [14] for both satellite as well as terrestrial links

Another specific advantage in using radiometric techniques for estimation of meteorological phenomena as well as their effects is the ability to generate accurate predictions through such methods even in dynamic network scenarios[14]. Radiometric measurements have been demonstrated to be accurate in a number of climatic conditions, as shown by researchers over the years[15]. Specific applications of accurate short-term meteorological event prediction have been demonstrated by a host of researchers[16] [17] [18]. Among the different parameters used, brightness temperature-based measurements have been found to yield highly accurate results[19].

The recent years have also seen the employment of novel modern algorithms and techniques for improvement of forecast accuracy, usually through employment of different machine learning techniques [20] [21]. Among the different categories of techniques, neural network-based methods have been found to yield highly accurate results [22] [23] [24].

Another recent novel work applied iterative gradient descent to effectively predict heavy rainfall related phenomena from ground-based radiometric data [25]. Another recent work used a least-squares based estimation to produce commendable results [26]. Two other recent works in this domain must be mentioned. [27] illustrates the application of low-complexity adaptive spline regression for prediction of rain events in the short-term, showing significant results. Another novel method based on classification and adaptive regression performs accurate determination of sky status from radiometric data [28].

The present work examines the recent work in the domain of radiometric prediction of meteorological phenomena, with a focus on rain events, and highlight significant research problems which can lead to enrichment of the field by solving critical issues related to accuracy and reliability of predictions. The survey of recent relevant literature in the domain follows the present section, and is divided into two subsections, on radiometric estimation and machine learning techniques respectively. The subsection on radiometric estimation consequently presents a survey of recent relevant work in the domain. The next subsection presents an intensive review of application of machine learning-based estimation techniques for rain-related phenomena. The following section outlines the major estimation methods employed by researchers in recent years. Simulation results are compared for some of the major methods in the following section, and the findings are discussed extensively. The paper is concluded by highlighting significant issues which can be addressed in the relevant domain.

## 2 Methodology

### 2.1 Survey of Radiometric Estimation Techniques

The estimation of occurrence of meteorological phenomena as well as the prediction of the effects of such phenomena on microwave and millimeter wave signals has been a significant area of interest for researchers since many years [1]. Corresponding sky status has been identified as a significant feature of interest in the evaluation, classification and estimation of meteorological phenomena, which is specifically significant for rain events [2] [3]. Among the many popular techniques and systems employed by researchers, radiometric measurements have yielded consistently accurate results [4] [5] [6].

Radiometric estimation of Integrated Water Vapour (IWV) allowed Hocke and others to accurately generate weather predictions, employing a time series model, using microwave radiometric measurements [4]. Moving average-based estimates are generated, employing the brightness temperature parameter, at 142 GHz. The opacity observed at 142 GHz is found to be significantly correlated with IWV as well as Integrated Liquid Water (ILW), considering high values of all the parameters. Bootstrapping is applied to increase the statistical stability of the proposed model. An important outcome of the research is the identification of the effects of missing or outlier data values on the accuracy of estimation, which highlights the need for dynamicity in such models. A fast-response optical rain gauge-based technique highlighted in a simultaneous study by Karmakar and others is employed for rain attenuation measurement considering IWV-based rain height estimation [5]. Excellent results were also obtained by Karmakar and others for ground-based radiometric measurements at 22.234 GHz [6]. The estimates for atmospheric water vapour obtained through radiometric measurements were found to agree to a close degree with actual values. The results obtained by such diverse groups of researchers indicate the general effectiveness and applicability of radiometric measurements in the estimation of meteorological phenomena through observation of corresponding parameters [15] [16] [18] [19].

The accurate statistical representation of the attenuation of microwave and millimeter wave signals due to rain events is crucial for satellite and terrestrial communication systems [7] [8]. The height of rain columns can be directly correlated to signal attenuation in most cases and geographical locations, with the effect being especially pronounced in extreme climates as found in tropical locations. As a consequence, multiple groups of researchers have proposed attenuation models for such locations which are found to significantly outperform traditionally employed models such as the ITU-R and Global Rain-rate models [8] [10] [11]. The trends identified by Ramachandran and Kumar have been validated by other researchers over the years [9] [18] [19], and clearly show the presence of breakpoints in the rain attenuation trends which are not detectable by the traditional models. Since such breakpoints are also used to demarcate between types of rain events of varying intensities, they hold special significance in terms of signal attenuation estimation for microwave and higher frequency band communication and telemetry systems. Rain rate and attenuation exceedance parameters are also shown to be highly correlated, from the results obtained by Ramchandran and Kumar, as well as other researchers in the domain [8] [9] [10] [12] [13] [17]. Further, the importance of the brightness temperature parameter has also been established in the context of accurate prediction of rain [8] [9] [19].

### 2.2 Statistical Methods and Machine Learning in Signal Attenuation Estimation

Over the years, the popularity of statistical methods for prediction of meteorological events has led to the adoption of machine learning and artificial intelligence-based techniques for such purposes. In this manner, existing models which have shown promise[6] [19] with some lacunae such as relatively low correlation coefficient values between parameters of interest, have been improved upon by the application of novel modern techniques, inclusive of neural network-based approaches. Superepoch analyses of time series data for multiple thermodynamic indices have been performed for accurate prediction of thunderstorms in recent years[16]. An interesting work in nowcasting of rainfall in tropical regions proposes a novel algorithm focusing on precipitable water vapour (PWV) variations to generate accurate estimates for rain events[21]. Factors such as seasonality of observed trends are taken into account, and the validation of the model is performed by comparing estimates with actual obtained values for multiple geographical locations. Another recent work of interest highlights an effective neural network-based estimation model for tropical regions, which can also be ported with minimum changes for other regions as well[24]. Markovian queuing is applied in another recent work[9] which shows impressive prediction results at microwave frequencies.

The estimation of signal attenuation due to rain events for satellite frequencies has been recently attempted in a significantly novel manner[12]. Shadowed-Rician (SR) fading is considered for land mobile satellite (LMS) channels, with M-ary phase shift keying being employed by the researcher. An important result achieved in the paper is the derivation of closed-form expressions for the corresponding moment-generating function, which allows reduction in error obtained by the joint-estimation scheme. The simulation results obtained by Arti are consequently substantiated by experimental methods. The experimental results agree to a significant degree with the values obtained through simulation.

Among the approaches explored in recent years, Zhang and others[23] have presented a dynamic region model for short-term rain forecasting using multilevel perceptrons, which yields accurate results in significantly dynamic weather scenarios. The greedy algorithm employed to dynamically configure the multilevel perceptron architecture is shown to consistently outperform other statistical and machine learning-based techniques with respect to parameters such as root mean square error (RMSE) and threat score. The researchers have therefore put forward a model that shows significant stability and accuracy in widely-varying climatic conditions, demonstrating the applicability and specific usefulness of neural network-based machine learning methods in meteorological estimation. Similar work has also been highlighted by other researchers in[22].

In this context, the recent work by Lu and others[14] is significant since it successfully attempts the modification of an established existing attenuation model (EXCELL) by machine learning techniques to incorporate dynamicity in the model at a significant level of accuracy, outperforming other established models such as ITU-R and Karasawa, as well as other country-specific models. The rain rate adjustment factor employed in this work is shown to be extremely effective in allowing accurate estimates for high and low intensity rainfall. The model proposed by Lu and others is also specifically significant since it is a unified model that allows the prediction of attenuation for both terrestrial as well as earth-space links.

The application of low-complexity machine learning methods with radiometric measurements is found to yield most promising results in recent years, with high accuracy and precision illustrated in both[25] and[26]. In particular, the work presented in[26] clearly demonstrates the benefits of combining machine learning techniques with standard statistical estimation, with significant increase in accuracy reported. The authors in[27] have applied low-complexity spline regression-based machine learning to accurately predict rain events in the short-term, with the technique achieving high accuracy (reflected by low RMSE).[28] presents another example of a recent successful application of regression-based machine learning for determination of rain events from sky status, with classification and regression being used in equal measure to draw the necessary inferences. Both[27] and[28] offer similar advantages, namely the combination of radiometric estimation and generation of machine learning-based estimates through the application of accurate and dynamic low-complexity techniques. The gains that such techniques offer can therefore be further observed through comparison of the performance of these techniques, which is presented in the following section.

## 3 Result and Discussion

As observed in the previous section, the combination of machine learning and radiometric estimation has yielded optimal results for some of the most recent research in the domain. Consequently, it is observed that the research outlined in[27] and[28] both involve the implementation of classification-based adaptive regression. Here the partitioning approach for the datasets reduces the worst-case time complexity of each method from $O(n^2)$ to $O(nlogn)$ or $O(n)$ depending on the randomness of the dataset (which is dependent on the variation of climatic conditions at the locations under observation). This is an improvement on the work outlined in[25] and[26], where the worst-case time complexity tends to $O(n^2)$ and a significant improvement compared to the complex iterative approach outlined in[14]. The different approaches are compared in the following Table 1.

**Table 1.** Comparative Performance of Estimation Techniques

| Technique | Worst-Case Time-Complexity | Error (RMSE) |
|---|---|---|
| Iterative Regression [14] | $O(n^k)$, $k>2$ | 0.05 |
| Backpropagation Neural Network [24] | $O(n^k)$, $k>3$ | 0.01 |
| Nonlinear Regression [25] | $O(n^k)$, $2<k<5$ | 0.028 |
| Adaptive Spline Regression [27] | O(n)logn | 0.02 |
| Adaptive Linear Regression [28] | O(n)logn ~ O(n) | 0.17 |

The relevance of the analysis is especially significant when the high degree of correlation (coefficients >0.88) is observed for the works outlined in [14], [27] and [28], compared to [24] and [25]. The study also sheds light on the high computational cost of neural network-based techniques arising out of their higher time complexities, with only modest gains in terms of accuracy, as reflected by the closeness of RMSE values achieved by the methods. Among the examined techniques, the adaptive linear regression-based method [28] has lowest time-complexity but comparatively high RMSE, for which the approach illustrated in [27] is observed to be more optimal. Therefore, it can be inferred that low-complexity machine learning techniques with significant model linearity would have optimally stable performance for the estimation of meteorological phenomena. The extant challenge is therefore to formulate and verify machine learning models running in near-linear time with accuracy approaching neural network-based models, which are often more suited to estimate significantly random phenomena (extreme weather variations in the present case).

## 4 Conclusion

This review work allows certain inferences to emerge from the significant body of research performed throughout the years in this domain. The prediction of meteorological events is found to have significant relevance to the estimation of wireless signal attenuation for microwave and millimeter wave frequencies. Parameters such as IWV and ILW are significant in predicting the occurrence of rain, and factors such as brightness temperature and exceedance therefore assume crucial importance in the process of estimation of signal attenuation in both the earth-space path as well as for terrestrial wireless microwave and millimeter wave links. The need for an accurate dynamic model is also evident from the research carried out, and low-complexity machine learning methods are expected to prove to be cheap and easy to implement for practical systems, as well as computationally inexpensive and efficient, even considering highly dynamic network scenarios in diverse geographical locations. Thus, statistical estimation of rain events and the correlation of such events with microwave and millimeter wave signal attenuation are expected to be explored in the domain, with specific emphasis on machine learning methods, which hold potential due to their robustness and versatility. As observed in the study, model linearity bears significant importance in terms of stability and improved error performance (low RMSE < 0.1). Hence there is a need to critically examine, explore and test low-complexity machine learning techniques to estimate rain events, especially for tropical regions where weather variations are much more significant than temperate regions.

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