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Research Article

Microwave Antenna Systems for Accurate Weather Monitoring in Solar Power Plants

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Abstract – Accurate and real -time weather monitoring is necessary for optimizing to the efficiency and reliability of solar energy. This paper examines the integration of the microwave antenna system for environmental sensing in the installation of solar photovoltaic (PV) systems, which focuses on their ability to detect large atmospheric variables such as cloud cover, humidity and rainfall. By using ground -based multichannel microwave radiometer (GMR), work with frequencies including 10 GHz, 18 GHz and 36 GHz, the system measures atmospheric brightness temperature (TB) to monitor the environmental conditions affecting solar radiation. A sun-tracking calibration method is used to ensure all weather operations, increase the accuracy and reliability of data acquisition. The architecture supports spontaneous integration with the existing plant infrastructure using a 915 MHz wireless telemetry and is scalable for both utility-scale and distributed photovoltaic systems. In addition, artificial neural networks (ANNs) are used to model nonlinear between TB data and solar cell outputs, enabling accurately short-term energy forecasting. The proposed approach supported by existing literature shows strong capacity to increase the operational plan, improve forecast accuracy and support intelligent energy management in solar systems. Limits and future directions, including phase-sensory antennas and hybrid sensor fusion, are also discussed.

Keywords – Microwave Radiometry, Solar Photovoltaic Systems, Weather Monitoring, Ground-Based Radiometers & Microwave Antennas.

I. INTRODUCTION

The global transition against renewable energy has made solar energy an important component to reduce the dependence on fossil fuels and reduce environmental pollution. solar photovoltaic (PV) systems, which converts sunlight directly into electricity, provides a scalable and durable solution to meet increasing energy requirements. However, the efficiency and stability of solar energy generation is very dependent on real -

time atmospheric conditions such as cloud cover, humidity and rainfall. Inaccurate weather forecasts can lead to suboptimal energy management, especially in large solar fields located in areas with rapidly changing weather patterns. Consequently, it is necessary to adapt to the exact and continuous weather monitoring of energy generation, forecasts performance variability and ensure the reliability of solar energy systems [1], [2].

Microwave antennas, which work within 1-100 GHz frequency range, act as important components for high -resolution environmental monitoring. These antennas act as a turn, and convert electrical signals to electromagnetic waves and vice versa, wireless communication and remote sensing. When it comes to solar power plants, microwaves are particularly valuable to capture atmospheric data under different weather conditions. Their ability to perform reliably in the presence of rain, fog and cloud intervention makes them ideal for continuous monitoring applications. Advanced antenna configuration-as phased arrays and parabolic reflectors—facilitate real-time beam steering, high directional benefits and wide-area coverage. These properties enable accurate detection of weather phenomena that influence solar irradiance. While circularly provided benefits of reducing polarized packed antennas signal reflections and deformation of more, they are often better for secondary data transfer than primary environmental sensation[3],[4],[5]. the suitability of different microwave antennas for weather monitoring in solar power plant applicationsIllustrates in Figure 1 below.

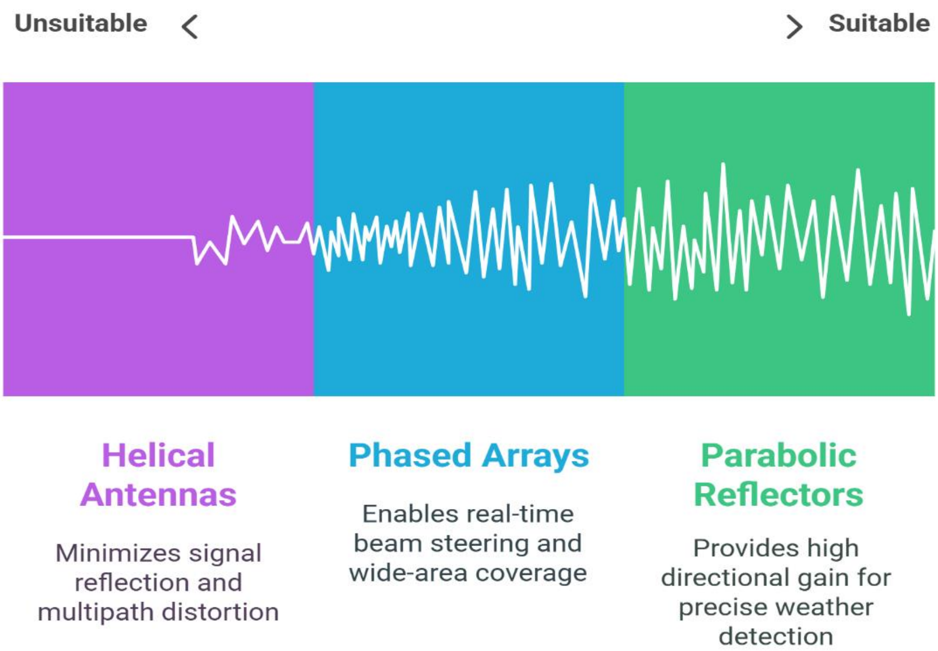

Fig. 1 Illustrates The suitability of different microwave antennas for weather monitoring in solar power plant applications

The relevance of the microwave antenna system in solar applications is reinforced through a series of leading studies. Narayanan and Bhonsle [6] first demonstrated the use of a radiometer of the Dicke-type with a parabolic dish at 2800 MHz to monitor the solar stream. introduced a solar signal -based adjustment and calibration technique for multichannel microwave radiometer, which improves operational stability[7]. developed a sun -tracking radiometric system, which is capable of estimating atmospheric channel atmosphere in all weather conditions, which enables continuous environmental data acquisition[8]. Corresponding Mattioli et al. (2017) applied microwave sensing to derive sun brightness temperature and cloud extinction profiles for atmospheric modelling in addition, Whitehurst et al. (2013) discovered the use of solar -driven microwave oven systems for environmental sensing, which highlights the potential for sustainable and autonomous monitoring. Overall, these studies reflect the increasing importance of microwave antenna systems to increase the accuracy of solar energy and operational flexibility [7], [8], [9], [10].

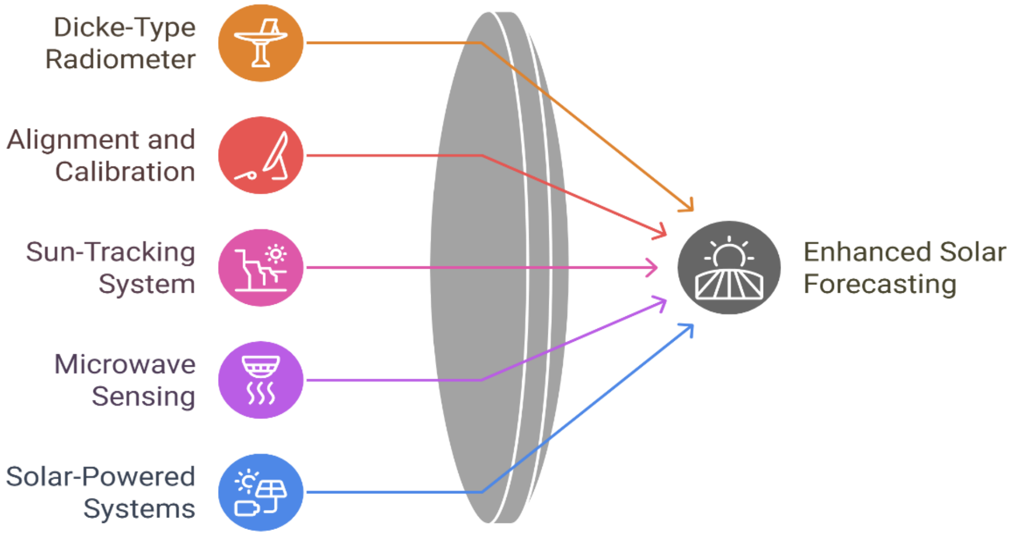

Fig 2. Explores new microwave antenna uses that improve solar energy prediction.

II. LITERATURE REVIEW

The integration of microwave antennae in solar energy systems for weather monitoring systems is inspired by the requirement for resilient and accurate sensing technologies. Original progress in microwave power transfer technologies was motivated by the concept of solar satellites, extended by Sasaki et al. [3] and Matsumoto [4]. These initial studies prepared the basis for understanding the propagation characteristics and efficiency of the microwave system over long distances, especially under different atmospheric conditions. Although it originally focused on the extra to like energy transfer was focused on microwave communication and robustness in adverse weather principles, terrestrial applications have been adapted since then, especially in solar energy infrastructure.

In a terrestrial context, the dynamic nature of atmospheric conditions presents challenges for photovoltaic (PV) efficiency. Solar energy production is very sensitive to cloud cover, humidity and rainfall, real -time, localized weather data is needed. Traditional meteorological instruments often lead to a lack of essential responsibility and coverage in solar farms. This difference has increased interest in microwave radiometry as a tool for weather monitoring. The leading work on Narayanan and Bhonsle [6] introduced 2800 MHz microwave oven to inspect the solar flux, where how can radiometric methods be used to monitor atmospheric conditions affecting solar output. Building on this, Lei et al. [7] showed that solar microwave radiation may be used to confirm system stability and antenna alignment, offering a non-intrusive and affordable way to keep ground-based multichannel microwave radiometers accurate. satellites to anticipate solar energy and support system stability. Figure 3 shows how microwave devices have evolved from being used in satellites to forecasting solar energy and aiding in system stability.

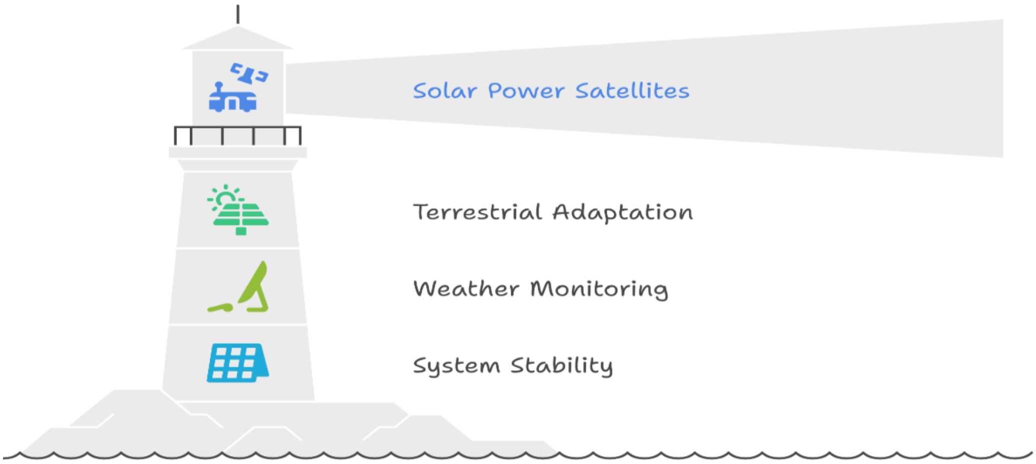

Fig. 3 demonstrates the growth of microwave devices from their use in satellites to solar energy forecasting and help with system stability.

Technological innovations have improved the possibilities of the microwave the radiometric system. Marzano et al. [8] suggested a sun-tracking microwave radiometer that measures air path attenuation in the Ka-, V-, and W-bands by switching its beam between the Sun and the sky background. This beam change technique enables accurate recovery of atmospheric attenuation parameters in all weather conditions, and offers a practical solution for continuous environmental monitoring. In addition, work and enhanced the vertical profile of atmospheric variables pertinent to solar irradiance forecasts by employing microwave radiometry to determine cloud extinction coefficients and sun brightness temperatures [9].

The antenna design plays an important role in the effectiveness of microwave -based weather monitoring systems. Circularly polarized packed antennas explored by [5] are known for their ability to reduce multiplication intervention and polarization mismatch, making them ideal for some communication functions within the monitoring of the solar farm. Meanwhile, the essential and phased array antennas make high profits and directional control, which allows for focused signal transmission and reception in broad areas. These properties are essential to achieve the spatial resolution and beam flexibility required for accurate environmental sensation in geographically dispersed solar arrays.
For environmental monitoring in solar energy systems. Figure 4 Microwave oven for environmental monitoring in solar systems shows the main components and growth of the radiometry.

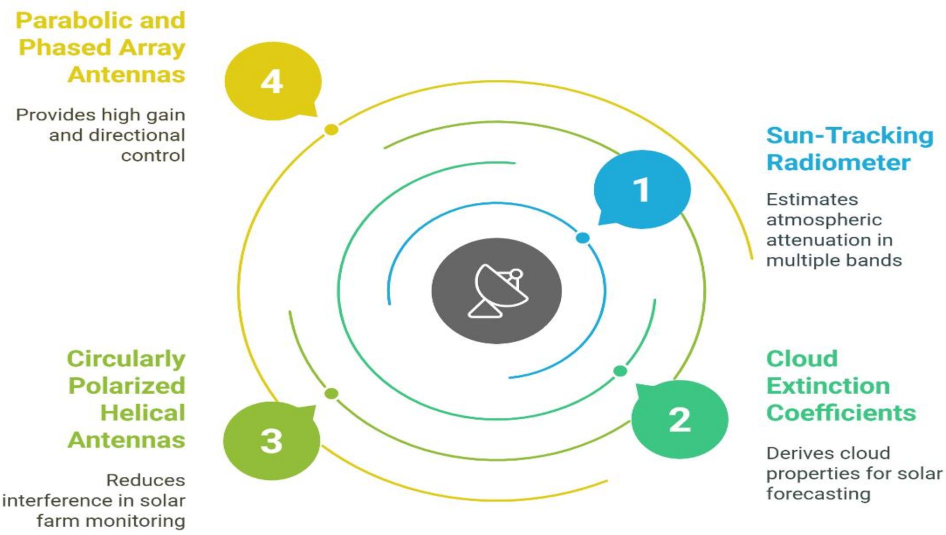

Fig. 4 illustrates key components and enhancements of microwave radiometry for environmental monitoring in solar energy systems.

Parallel to hardware progression, the use of artificial intelligence in combination with microwave sensing has attracted attention to solar forecasting. Ahmed et al. [1] and Bihi and Karasu [2] investigated artificial intelligence (AI)-based models, such as artificial neural networks (ANNs), which use radiometric and historical weather data to increase prediction accuracy. These models can learn complex ratios between atmospheric variables and solar output, which can enable active energy management. When the microwave in real-time is combined with sensing data, the AI-enhanced system provides a powerful platform for daily and intra-hour solar energy forecasting, supporting both operational decision-making and grid stability. In summary, literature reflects a progressive change for integrated, intelligent and scalable systems more than an ideological and experimental foundation. The convergence of advanced antenna technology, radiometric methods and machine learning have created new opportunities to distribute weather-resilient solar systems. This development not only improves the reliability of power generation in variable climate, but also corresponds to smart grid growth and widespread goals for renewable energy [7] - [10]. It can be seen from Figure 5 that AI and microwave observations help increase the accuracy of predicting solar output.

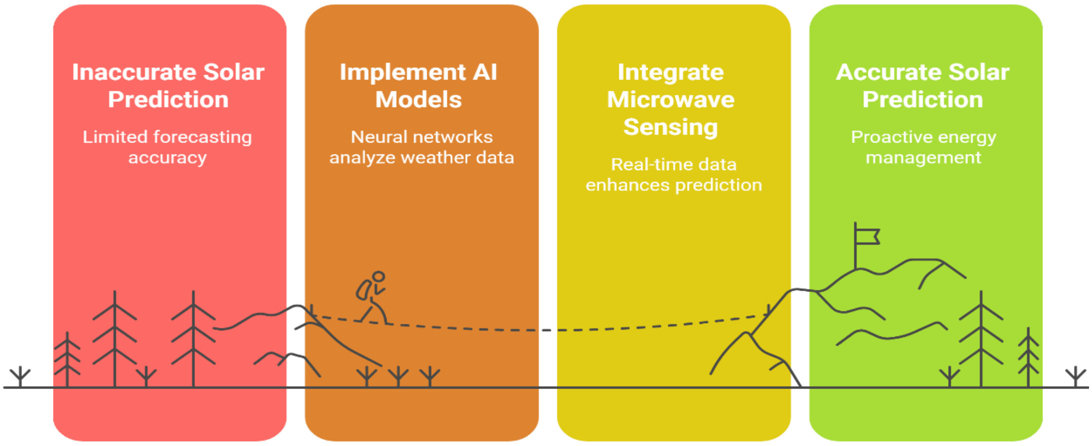

Fig. 5 Shows that AI and microwave measurements can enhance the accuracy of forecasting solar energy output.

III. METHODOLOGY

The study presents a systematic approach to integrate the microwave antenna -based remote sensing into weather monitoring frameworks at solar energy. The function benefits from both satellite and ground-based microwave radiometer, with the functioning data-driven and AI-enhanced forecasting models.

A. Microwave Radiometry for Atmospheric Monitoring

The study uses a theoretical approach in the microwave radiometry to monitor atmospheric parameters that affect the efficiency of the solar power plant. Ground-based multichannel microwave radiometer (GMR) is used to inspect the Earth's atmospheric column by measuring brightness (TB) in the areas, especially on the various frequencies, in the K-band (18-27 GHz) and V-band (40-75 GHz). These radiometers are able to detect atmospheric water vapor, liquid water content and temperature variation - all of which are important for understanding solar radiation fluctuations [7]. The system includes a parabolic reflection, feedhorn, heterodyne receivers and motorized elevation over-Azimuth mounting, which enables precise and repeatable scanning over time. These sensors provide continuous data collection in all weather conditions, ensuring atmospheric awareness of real -time for atmospheric awareness for solar energy. Systems for monitoring the atmosphere using radiation. Figure 6 shows the important parts and functions of microwave radiometry systems created for atmospheric monitoring.

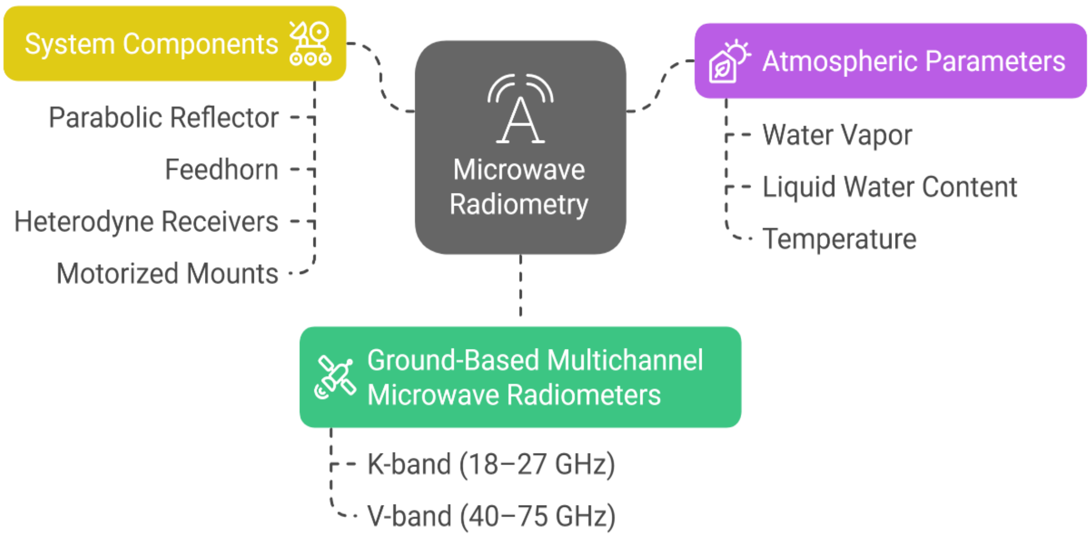

Fig. 6 illustrates the key components and capabilities of microwave radiometry systems for atmospheric monitoring.

B. Sun-Tracking Calibration and Signal Processing

The proposed system consists of a calibration method that uses the sun as a source of reference. Through a beam -switching strategy, the radiometer optimizes the possibility of pointing to the sun and a nearby region of clear sky, enabling the atmospheric channel estimates based on the opposite in the obtained TB signals. This method is very effective in variable season and supports continuous calibration without the need for artificial sources [2]. To improve the strength of this calibration, the Langley method is used under clear-sky conditions to estimate effective brightness temperature. Solar signal tracking also aids in confirm the alignment and angular accuracy of the antenna system over time [7]. These techniques together ensure that the radiometer maintains its measuring integrity under different environmental conditions. The process of calibrating the dish for tracking the sun is shown in Figure 7.

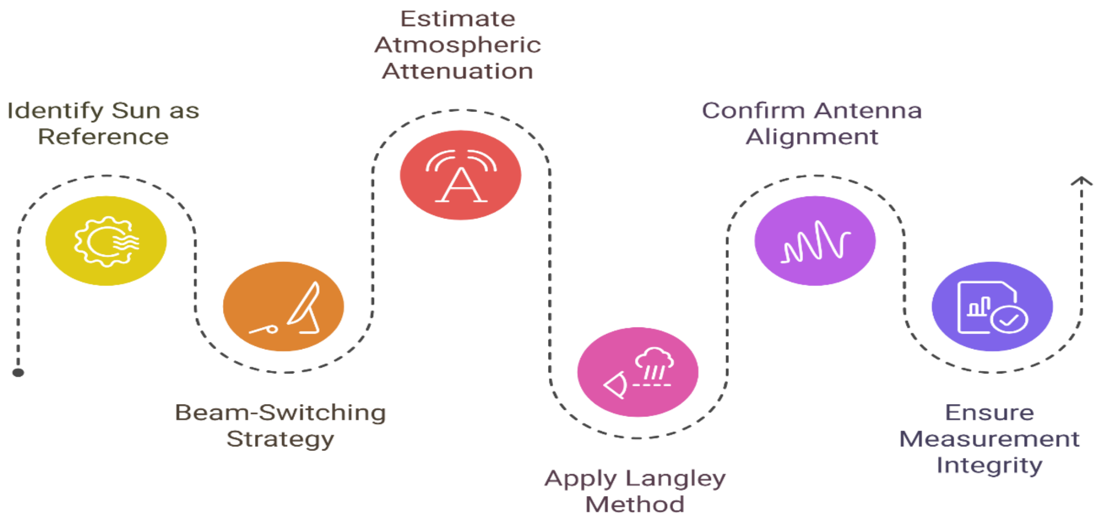

Fig. 7 illustrates the sun-tracking calibration steps for accurate antenna alignment and data integrity.

C. Integration with Solar Infrastructure

The conceptual design of the monitoring system emphasizes the minimum disruption in the existing PV system setup. GMR is proposed to install in strategic places such as central monitoring stations or high-pole mounts to maximize atmospheric visibility while avoiding the panel. The system architecture is designed to operate autonomously and is integrated with supervisory management and data acquisition (SCADA) system. For data transfer, a wireless telemetry module that works at 915 MHz is used, combined with monopole or helical antenna to facilitate stable communication between sensor nodes and control units [11]. In addition, solar-powered telemetry and data collection devices are included in external or off sites to ensure energy autonomy and flexibility[10]. This modular layout supports scalability in different plant sizes and geographical settings.As Figure 8 indicates, microwave radiometry works alongside solar systems, handling installation, communication and power independence.

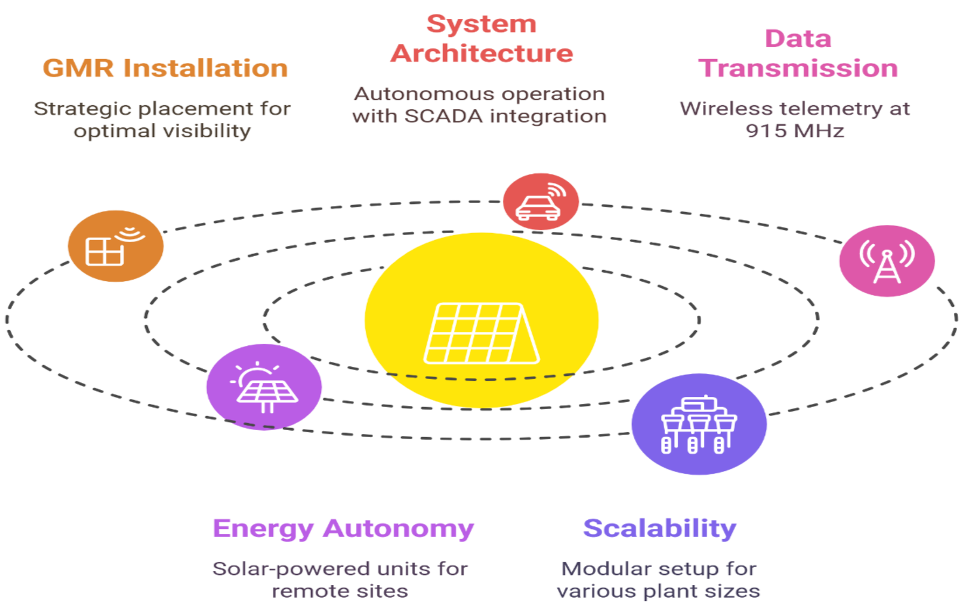

Fig. 8 Demonstrates how microwave radiometry fits into solar infrastructure, with an emphasis on setup, communication and being energy independent.

D. Frequency Band Selection and AI Forecasting

Microwave frequencies are carefully chosen based on their sensitivity to specific atmospheric variables. Frequency such as 10 GHz, 18 GHz and 36 GHz are especially responsible for water vapor, raindrops and cloudy density-they make ideal for solar-related weather monitoring [12]. The TB data collected on these frequencies is treated using radiation transfer models for ignorance, cloud -optic thickness and potential solar flux reductions. These extracted features are then inputs in an artificial neural network (ANN) model, which is trained on historical data to predict solar energy output. ANN is structured with several hidden layers and uses backpropagation for optimization. It is valid by using metrics such as mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2), ensuring high levels of high levels in short -term solar production forecast [1],[2].

E. System Evaluation and Limitations

The performance of the proposed system is evaluated through theoretical modelling and benchmark meteorological data. The most important assessment criteria include spatial resolution, signal- -noise ratio, antenna beam width-heavy and system latency. These parameters are evaluated under different atmospheric conditions using historical GMR data sets and simulated operating scenarios. Despite its strength, the system is facing limitations including signal attenuation during intense precipitation, calibration operation during long operating periods and deployment costs for large installations[7],[8]. In addition, high - frequency bands are more prone to resolution, and require data spills with signal correction algorithms or satellite radiometric data. Future research will focus on implementing phase -array antenna for agility, developing data modules with lightweight edge for real-time analytics, and detect the hybrid sensation network that combines microwaves, optical and infrared systems for comprehensive environmental monitoring. The balance between the main advantages and disadvantages of microwave radiometry devices for solar weather monitoring is shown in Figure 9.

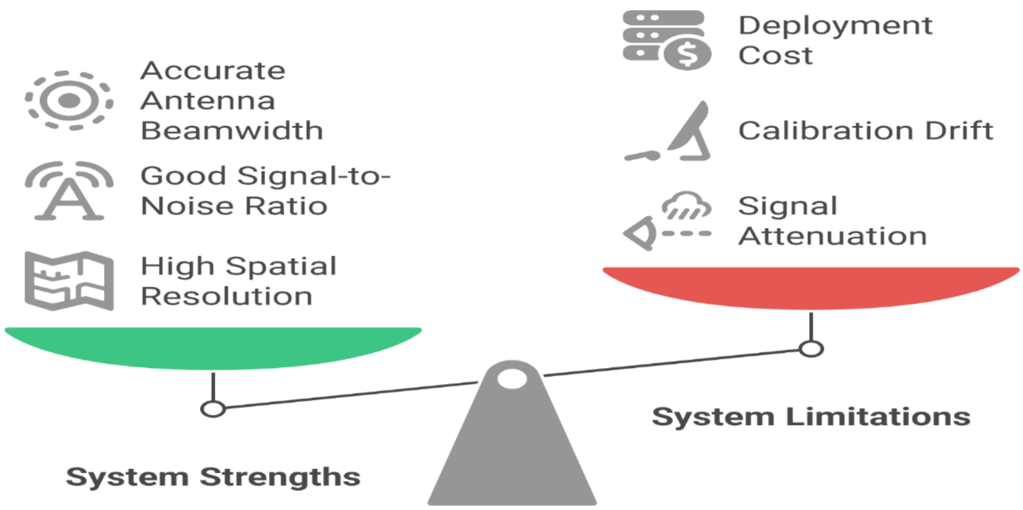

Fig. 9 shows strengths and limitations of microwave radiometry.

IV. RESULTS AND DISCUSSION

Analysis of microwave frequency performance in atmospheric monitoring applications reveals significant correlations between specific frequency bands and significant weather variables affecting the solar photovoltaic (PV) systems output. Frequencies such as 10 GHz, 18 GHz and 36 GHz are particularly effective for detecting changes in the intensity of atmospheric water vapor, sky optical thickness and rainfall - which directly affects the variation of solar irradiance received by PV modules [12]. Of these, 10 GHz has emerged as the strongest in different weather conditions, which still offer stable signal integrity, and captured relevant environmental changes. High frequencies such as 36 GHz provide better spatial resolution, but are subject to heavy rain or dense clouds under the cover. The use of sun - tracking microwave radiometry described and improves the efficiency of the system by providing a constant, passive and self -calibrating method of monitoring atmospheric attenuation. This approach enables continuous data acquisition even in non-ideal weather, which makes it very suitable for solar energy and real-time and solar energy[8].the relationship between microwave frequency bands and weather observation, attenuation of signals and solar impact is depicted in Figure 10 below.

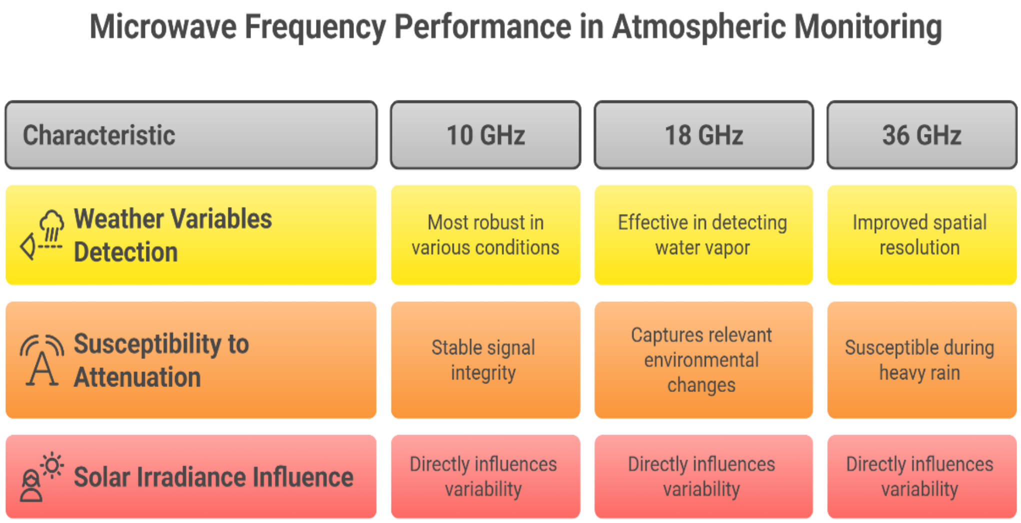

Fig. 10 compares microwave frequency bands in terms of weather detection, signal attenuation, and solar irradiance influence.

System integration ideas suggest that microwave radiometry can be effectively incorporated in the operating framework of solar power plants with minimal structural or operating intervention. The radiometer can be installed strategically dedicated poles, rooftops of control units, or without inverter, or without casting shadows the solar cell system. The use of 915 MHz wireless telemetry modules enables reliable data transmission with low oppression between sensors and central control units, which facilitates spontaneous integration with SCADA systems in advance in most utility-scale solar installations [11]. In addition, application of solar -powered telemetry units, as suggested in [10] increases the system's autonomy, making it viable for distribution in off-network or remote environment. When combined with artificial neural networks (ANN), the keys enable the microwave frequencies to model the future of temperature data with the short term. On such data, trained ANN models have shown significant improvement in the forecasting accuracy by learning complex nonlinear relationships between complex, atmospheric conditions and power generation trends [1],[2]. This integration supports a change to smart, data-driven energy management systems in the solar sector.

Despite these promising consequences, several limitations should be taken up to ensure the broader applicability and reliability of the proposed system. Microwave signals with high existence, while high -resolution are insecure to indicate a decline in thunderstorms such as profitable, especially thunderstorms for atmospheric sensation. This can reduce the accuracy in reading the brightness temperature and as a result in predictions for solar output. In addition, while the sun -tracking calibration method reduces the need for maintenance, the long -term system accuracy depends on the mechanical reliability of tracking components and the stability of solar observations. Economic ideas are also significant multi-channel channel radiometer and advanced antenna systems represent significant capital investments, which limit the adoption between solar operators on a potentially small and medium scale. Future enhancements should focus on the development of low costs, compact phase-array antenna, as well as edge computing options for on-site processing. The combination of microwaves, infrared and optical sensors can also improve hybrid data merger models and expand the utility of the system into different climate regions and solar farm typology and solar farm typologies. Figure 11 presents details on the appropriate microwave antennas for monitoring weather in solar power plant projects.

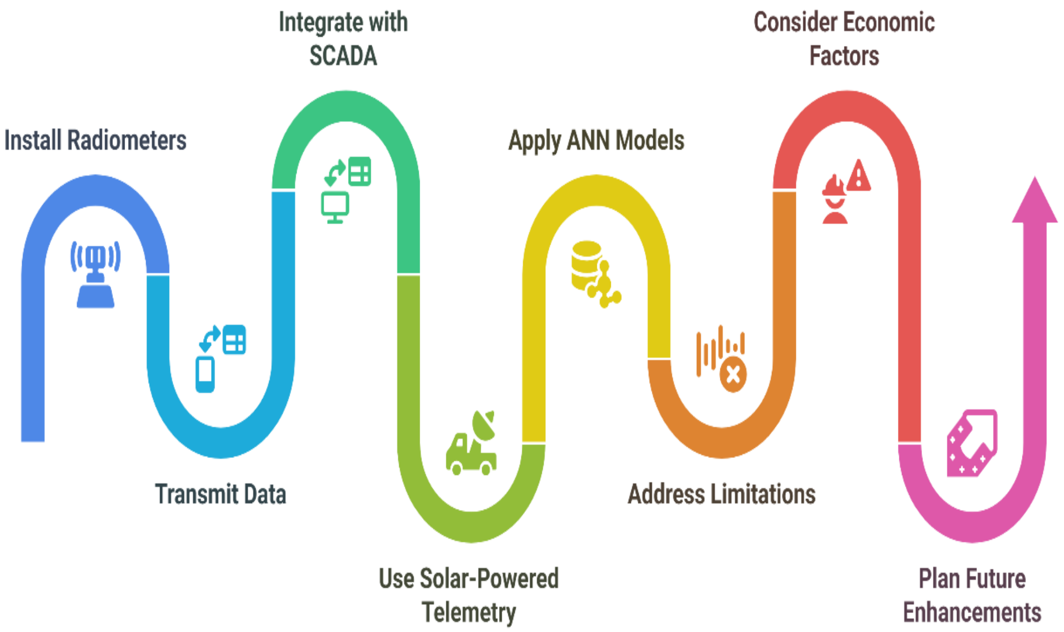

Fig. 11 It describes the process of incorporating microwave radiometry in solar plants, starting with installation and including future improvements.

V. CONCLUSION

The This research demonstrates a microwave antenna system-particularly a strong capacity of ground-based radiometer to increase the accuracy and resilience of weather wake monitoring in solar power plants. By operating in larger microwave frequencies such as 10 GHz, 18 GHz and 36 GHz, the system detects and interprets critical atmospheric parameters including water vapor, cloud cover and rainfall. Implementation of sun tracking radiometry enables all weather calibration and data acquisition, which is necessary to maintain the consistent solar radiation forecasting. The proposed architecture is modular, autonomous and scalable, making it suitable for integration with both utility-scales and distributed PV systems. Compatibility with wireless telemetry, energy autonomous operation and SCADA frameworks ensure practical deployment in different environments. In addition, the integration of artificial neural networks (ANNs) allows advanced forecasting by modelling nonlinear relationships between atmospheric data and PV output. This approach supports predictive grid management and improves the general stability and efficiency of solar energy systems.

Despite the strength, the system faced challenges including serious weather conditions, mechanical calibration addiction and preliminary distribution costs, including signal attenuation. To address these limits, the antenna will be necessary for future function, edge AI integration and hybrid sensor fusion. Nevertheless, conclusions confirm that microwave antenna systems, when intelligently implemented can play an important role in promoting the weather resilient and data-driven strategies for solar energy.

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