

Cosmicpulse AI: Intelligent Detection and Visualization of Radio Signal

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Abstract:

Radio frequency communication systems generate massive amounts of signal data continuously through satellite communication, radar systems, wireless transmission, and astronomical observations. Monitoring these signals manually is difficult because of environmental noise, interference, and rapidly changing signal patterns.

Traditional monitoring systems mainly rely on threshold-based methods that fail to detect complex anomalies accurately in real time.

The proposed system, “CosmicPulse AI: Intelligent Detection and Visualization of Radio Signal,” introduces an Artificial Intelligence based approach for intelligent signal monitoring and anomaly detection. The system processes pulsar signal datasets using advanced signal preprocessing techniques such as Butterworth Low-Pass Filtering and Savitzky-Golay smoothing. After preprocessing, Long Short-Term Memory (LSTM) neural networks and Isolation Forest algorithms are used to identify abnormal signal behavior and unexpected frequency variations.

The system is developed using Python and Streamlit to provide an interactive real-time monitoring dashboard. Features such as signal overview graphs, anomaly analysis, live noise filtering, 3D radio wave visualization, burst tracking maps, and automated system alerts improve signal interpretation and monitoring efficiency. The proposed system can be effectively applied in radio astronomy, satellite communication monitoring, wireless spectrum sensing, and intelligent signal security analysis.

Keywords: Radio Signal Processing, Artificial Intelligence, LSTM, Streamlit, Isolation Forest, Signal Visualization, Anomaly Detection

I. INTRODUCTION

Modern communication systems heavily depend on radio frequency transmission for wireless communication, radar systems, satellite networks, and scientific space observations. Large amounts of signal data are generated every second, making manual monitoring highly difficult and inefficient. Environmental interference, atmospheric disturbances, and unauthorized transmissions further increase the complexity of radio signal analysis.

Traditional signal monitoring systems mainly use static threshold techniques and manual analysis methods. These systems are unable to identify hidden anomalies efficiently and often produce inaccurate results in noisy environments. As communication technologies continue to evolve, there is a growing need for intelligent systems capable of processing

and analyzing signal data automatically in real time.

To overcome these limitations, the project “CosmicPulse AI” was developed as an intelligent radio signal monitoring platform. The system integrates signal preprocessing, Artificial Intelligence based anomaly detection, and real-time visualization into a single web application. Butterworth filtering and Savitzky-Golay smoothing algorithms are used to remove signal noise and improve waveform quality. LSTM neural networks and Isolation Forest algorithms are employed to detect abnormal signal behavior and classify anomalies automatically.

The application is developed using Python and Streamlit, providing a lightweight and interactive dashboard for signal monitoring. The system also includes real-time visualizations such as signal overview graphs, 3D radio wave surfaces, burst tracking maps, and automated alert systems for high-severity anomalies.

The proposed solution improves monitoring accuracy, reduces manual effort, and provides intelligent analysis for radio signal environments.

II. RELATED WORK

Radio frequency signal monitoring and anomaly detection have gained significant attention due to the increasing use of wireless communication systems, satellite networks, and spectrum-dependent technologies. Researchers have proposed several techniques to improve signal analysis accuracy and reduce manual monitoring efforts.

Traditional radio signal monitoring systems primarily relied on threshold-based detection methods, where alerts were generated whenever signal strength exceeded predefined limits. Although simple to implement, these systems were unable to identify complex anomalies and often generated false alarms in noisy environments.

With the advancement of machine learning, intelligent anomaly detection techniques have been introduced. Algorithms such as Isolation Forest and Support Vector Machine (SVM) have been widely used to detect unusual signal behavior by identifying outliers within large datasets. These methods improved detection performance compared to traditional statistical approaches.

Recent studies have focused on Deep Learning models such as Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM) networks for analyzing time-series radio signals. LSTM models are particularly effective because they can learn temporal patterns and detect subtle deviations in signal behavior over time. This capability makes them suitable for applications involving satellite communications,

spectrum sensing, and wireless security monitoring.

Several modern systems also incorporate signal preprocessing techniques such as Fast Fourier Transform (FFT), Butterworth Filtering, and Savitzky-Golay Filtering to remove noise and improve signal quality before analysis. These techniques help machine learning models achieve higher detection accuracy.

Despite these advancements, many existing systems focus only on anomaly detection and lack comprehensive visualization and alerting capabilities. Most solutions provide basic graphical outputs and require expert knowledge for interpretation. Real-time geographical tracking, interactive 3D visualization, and automated notification mechanisms are often absent.

The proposed CosmicPulse AI system extends existing research by integrating advanced signal preprocessing, LSTM-based anomaly detection, FFT analysis, interactive 3D radio wave visualization, live burst tracking maps, and automated email alert mechanisms into a single user-friendly platform. This approach improves monitoring efficiency, visualization quality, and response time for radio signal anomalies.

III. SYSTEM OVERVIEW

This project, titled "CosmicPulse AI: Intelligent Detection and Visualization of Radio Signal," aims to design and develop a powerful, real-time, and user-friendly web application for automated signal monitoring. The system is built using Python and Streamlit, integrating modern Machine Learning tools like LSTM (Long Short-Term Memory) and Isolation Forest to classify signal pulses and detect anomalies accurately. In the modern digital era, protecting the RF spectrum is critical for national security and reliable communication. As more devices connect wirelessly, there is a growing demand to extract meaningful insights from signal bursts. This project addresses that need by providing a practical solution that is accurate, automated, and accessible to both technical and nontechnical users. The application allows users to: Analyze Pulsar Datasets: Process complex signal sequences from CSV files. Remove Noise Automatically: Apply advanced mathematical filters like Butterworth and Savitzky-Golay. Detect Unauthorized Pulses: Use AI to flag anomalies that don't follow standard patterns. Once data is processed, it undergoes deep learning analysis, after which results are presented in the form of interactive 3D visualizations—such as wave surfaces and heatmaps—enabling users to quickly interpret signal behavior. This tool has applications across various domains such as:

- Satellite Communication Security
- Radio Astronomy Research
- Wireless Interference Monitoring
- Unauthorized Transmission Detection

The final output is a lightweight, open-source, web-based application that requires no complex setup to operate, making it an ideal solution for security officers, students, and researchers.



IV. MODULE DESCRIPTION

1. Signal Preprocessing Module

In this module, the primary objective is to improve the quality and reliability of the captured radio signals before further analysis. Environmental disturbances, background noise, and signal fluctuations may affect the accuracy of anomaly detection. To overcome these challenges, the system applies advanced preprocessing techniques such as Butterworth Low-Pass Filtering and Savitzky-Golay smoothing.

The Butterworth filter removes unwanted high-frequency noise while preserving the essential characteristics of the signal waveform. Simultaneously, Savitzky-Golay smoothing enhances signal clarity by reducing random variations without distorting important waveform patterns. These preprocessing methods ensure stable and clean signal data, thereby improving the overall efficiency and accuracy of the Artificial Intelligence-based detection system.

2. Signal Normalization Module

In this module, the cleaned radio signals are normalized to maintain consistent data representation for Artificial Intelligence processing. Signal values may vary significantly due to changes in signal strength, environmental conditions, or device sensitivity. Such variations can negatively impact model performance and reduce detection accuracy.

To address this issue, Min-Max normalization techniques are applied to scale the signal values within a standardized range. This normalization process improves data consistency and enhances the learning capability of machine learning and deep learning models. As a result, the system achieves better stability, faster convergence, and more reliable anomaly classification.

3. FFT Processing Module

The FFT Processing Module focuses on transforming radio signals from the time domain into the frequency domain using the Fast Fourier Transform (FFT) algorithm. Frequency-domain analysis helps reveal hidden signal characteristics and abnormal spectral behaviors that may not be visible in the original waveform.

By analyzing the frequency spectrum, the system can identify unusual frequency spikes, interference patterns, and irregular signal distributions. FFT processing enables

more accurate feature extraction and improves the detection of suspicious or abnormal radio signal activities. This module plays a crucial role in identifying complex signal anomalies efficiently.

4. AI Anomaly Detection Module

In the AI Anomaly Detection Module, advanced Artificial Intelligence algorithms are utilized to automatically analyze radio signal behavior and detect abnormalities. The system employs Long Short-Term Memory (LSTM) Networks to study sequential signal patterns and learn temporal dependencies within signal data.

Additionally, Isolation Forest algorithms are used to identify unusual signal activities by isolating anomalous patterns from normal behavior. These AI models continuously monitor incoming signal streams and classify abnormal conditions with high accuracy. The module significantly reduces manual monitoring efforts and enhances real-time anomaly detection performance.

5. Visualization Module

The Visualization Module is designed to provide graphical representations of radio signal analysis and anomaly detection results. Effective visualization helps users understand signal behavior, monitor live processing activities, and identify abnormal conditions more efficiently.

The module displays Signal Overview, Live Signal Filtering, Anomaly Detection Analysis, 3D Radio Wave Visualization, and Burst Tracking Maps. These visual outputs present both time-domain and frequency-domain information in an interactive manner. The visualization system improves situational awareness and assists researchers or monitoring personnel in interpreting signal patterns in real time.

6. Alert Management Module

In this module, the system generates automated alerts whenever critical anomalies or suspicious signal activities are detected. Alert notifications help users respond quickly to abnormal events and maintain continuous monitoring efficiency.

The generated alerts include important information such as anomaly category, severity level, timestamp, detected frequency range, and recommended actions. All alert details are stored in structured JSON log files for future analysis and record maintenance. For high-severity anomalies, the system can trigger automated notification messages to ensure immediate attention and rapid response to potential signal threats.

V. METHODOLOGY

The methodology of CosmicPulse AI consists of multiple stages including signal acquisition, preprocessing, frequency analysis, Artificial Intelligence-based anomaly detection, visualization, and alert generation. These stages work together to provide accurate monitoring and detection

of unusual radio signal patterns.

Initially, pulsar and radio signal datasets are loaded from CSV files and validated to ensure data consistency. The acquired signals may contain noise and unwanted fluctuations caused by environmental interference and sensor limitations. To improve signal quality, Butterworth filtering and Savitzky-Golay smoothing techniques are applied during the preprocessing stage.

After noise reduction, the cleaned signal is normalized to maintain a uniform data range and improve the performance of machine learning models. The normalized signal is then converted from the time domain to the frequency domain using Fast Fourier Transform (FFT). This transformation helps identify important frequency components and hidden signal characteristics that may not be visible in the original waveform.

The extracted features are analyzed using Artificial Intelligence algorithms such as Long Short-Term Memory (LSTM) networks and Isolation Forest. The LSTM model captures temporal dependencies and sequential signal behavior, while the Isolation Forest algorithm detects outliers and unusual patterns. The combination of these techniques improves anomaly detection accuracy and reduces false positives.

Detected anomalies are visualized through an interactive Streamlit dashboard. Various visualization techniques including line graphs, frequency spectrum plots, heatmaps, anomaly trend charts, and 3D radio wave surface plots are used to provide detailed insights into signal behavior. The system also includes burst tracking maps that help users monitor the occurrence and movement of unusual signal events.

To enhance monitoring capabilities, CosmicPulse AI continuously evaluates anomaly severity levels. When detected anomalies exceed predefined thresholds, automated alert notifications are generated. These alerts are recorded in JSON-based history logs, enabling future analysis, event tracking, and performance evaluation of the system.

Overall, the proposed methodology integrates signal processing, machine learning, and real-time visualization techniques to provide an efficient and intelligent platform for radio signal anomaly detection and monitoring.

VI. REQUIREMENTS SPECIFICATION

Requirement Specification is an important phase in system development that defines the hardware and software components needed for the successful implementation of the project. It provides detailed information about the system requirements, development environment, tools, and resources required for smooth execution. Proper requirement specification helps ensure system stability, performance, and efficient project development.

Software Requirements

Software requirements refer to the programs, libraries, frameworks, and development tools required for implementing the system. These include the operating system, programming language, IDE, machine learning libraries, and visualization tools. Proper software configuration helps achieve accurate processing, efficient development, and stable system performance.

Table -1 Software Requirements

SOFTWARE COMPONENT	SPECIFICATION
Operating System	Windows 10/11 (64-bit)
Programming Language	Python3.9+
Integrated Development Environment(IDE)	VS code/Pycharm
Web Framework	Streamlit (version 1.20+)
Deep Learning Library	TensorFlow/Keras (for LSTM)
Machine Learning Library	Scikit-Learn (for Isolation Forest)
Signal Processing Library	SciPy (Butterworth & Savgol Filters)
Data Manipulation	NumPy & Pandas
Visualization Tools	Plotly (for 3D Graphs)

Hardware Requirements

Hardware requirements refer to the physical components needed to run the proposed system effectively. These components include processor, RAM, storage devices, monitor, and network connectivity. Proper hardware configuration ensures smooth performance, faster processing, and efficient execution of the application.

Table -2 Hardware Requirements

HARDWARE COMPONENTS	SPECIFICATION
Processor	Intel Core i5 or higher
RAM	8 GB or Above
Hard Disk	256 GB SSD
Monitor	15" Color Monitor
Input Devices	Standard keyboard & mouse
Network Connection	High-speed Internet
Graphics Card	Integrated Graphics

VII. SYSTEM IMPLEMENTATION

IMPLEMENTATION PHASES

System Implementation is the stage where the theoretical design is converted into a working software system. It involves configuring, integrating, coding, testing, and deploying the complete application for real-world use. For the CosmicPulse AI project, the implementation phase focused on translating the signal processing and AI architecture into a fully functional and user-friendly Streamlit-based web application.

- Convert the proposed design into a working solution using Python and Streamlit.
- Ensure seamless integration between signal data input, noise filtering, AI anomaly detection, and 3D visualization.
- Provide a lightweight, interactive web interface accessible to both technical and security personnel.

1. Environment Setup

- Installed required libraries such as: streamlit – for the web interface.
- pandas, numpy – for large-scale signal data handling and manipulation.
- scipy, filterpy – for implementing Butterworth and Savitzky-Golay mathematical filters.
- tensorflow/keras, scikit-learn – for loading the LSTM Network and Isolation Forest models.
- plotly – for generating interactive 3D wave surfaces and heatmaps.
- Developed in Python 3.x, using VS Code as the primary IDE.

2. Module Development

- Each functional module was implemented in Python:
- Data Ingestion: Developed a module to process Pulsar Datasets (Time-Series Radio Data) from CSV uploads.
- Signal Preprocessing: Implemented noise reduction using Butterworth filters and peak preservation using Savitzky-Golay filters.
- AI & Intelligence Engine: Integrated the LSTM network for sequential signal analysis and Isolation Forest for outlier detection.
- Automated Security Layer: Created an alert module that triggers an email notification via SMTP when a "CRITICAL" signal is detected.

3. Streamlit Interface Integration

- Created an interactive, real-time UI using Streamlit widgets:
- File uploaders for CSV signal data.
- Side panels for navigation and adjusting model sensitivity sliders.
- Real-time feedback dashboard displaying "Points Processed" and "Detected Anomalies."

4. Testing & Debugging

- Unit and integration testing conducted for the filtering and AI modules.
- Verified handling of edge cases like corrupted CSV files or extreme signal bursts.
- Visual components tested for responsiveness across different screen sizes.
- The application can be deployed locally by running streamlit run app.py or hosted on Streamlit Cloud for remote access via a web browser.

VIII. SAMPLE OUTPUT



Fig -2 Dashboard Page



Fig -3 Anomaly Detection



Fig -4 Live signal & Noise filtering

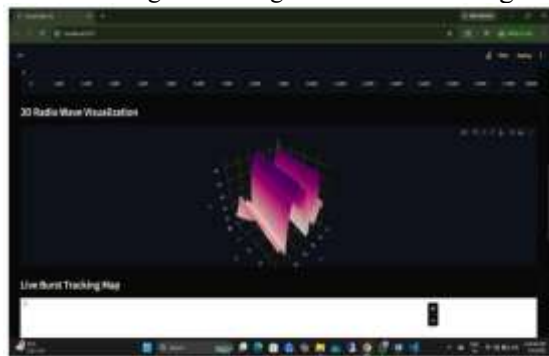


Fig -5 3D Wave Visualization

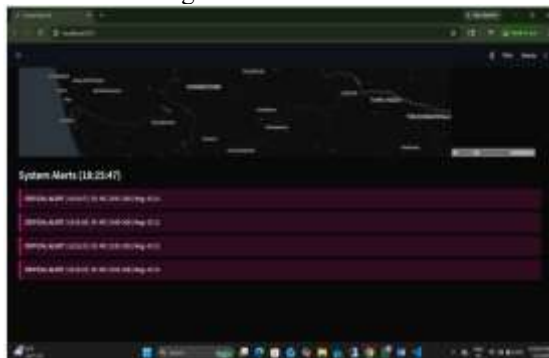


Fig -6 Sysstem Alerts

IX. CONCLUSIONS

The project "CosmicPulse AI: Intelligent Detection and Visualization of Radio Signal" has been successfully designed and developed as a robust, real-time solution for the automated monitoring of radio frequency signals. In an era where the RF spectrum is becoming increasingly crowded, this system provides a critical bridge between complex signal data and actionable intelligence.

By integrating advanced mathematical filters like Butterworth and Savitzky-Golay, the system effectively handles environmental noise, ensuring that signal integrity

is maintained for analysis. The core intelligence, powered by a hybrid AI approach using LSTM Networks and Isolation Forest, demonstrates high efficiency in learning sequential signal patterns and accurately flagging unauthorized or anomalous transmissions that could signify security threats or scientific discoveries.

The implementation of an interactive Streamlit dashboard equipped with 3D Wave Surface and Heatmap visualizations ensures that complex technical data is accessible to both expert researchers and non-technical security officers. Furthermore, the automated SMTP Alert Module and JSON Logging system ensure that no critical event goes unnoticed, providing a secure audit trail for future forensic analysis.

Overall, CosmicPulse AI stands as a scalable, open-source, and efficient tool that addresses the modern challenges of satellite security, radio astronomy, and wireless interference monitoring. The project successfully meets all its initial objectives, delivering a high-performance application that is ready for deployment in real-world signal monitoring environments.

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