GLOBAL MANGROVE WATCH: RADAR ALERTS FOR MANGROVE MONITORING (RAMM) PROJECT

FINAL REPORT

June 2025

Prepared for:

European Space Agency

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LIST OF ACRONYMS

API	Application Programmatic Interface
ATBD	Algorithm theoretical basis documents
C-DAS	Copernicus Data Access System
CNN	Convolutional Neural Network
DGES	The Department of Geography and Earth Sciences, Aberystwyth University
ESA	European Space Agency
FAIR	Findable, accessible, interoperable, reproducible principle
GMA	Global mangrove alliance
GMW	Global Mangrove Watch
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
MAMM	Multi-sensor alerts for mangrove monitoring
MMU	Minimum Mapping Unit
NDPI	Normalised difference polarisation index
NGO	Non-governmental organization
RADD	Reverse-Then-Add algorithm
RAMM	Radar Alerts for Mangrove Monitoring
SAR	Synthetic aperture radar
VH	Vertical transmit horizontal receive polarisation
VV	Vertical transmit vertical receive polarisation

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Issue	Description	Date	Authored & approved by
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1.0 INTRODUCTION

The *Global Mangrove Watch: Radar Alerts for Mangrove Monitoring (RAMM) project* was a 15-month collaboration between Hatfield Consultants (Hatfield), Aberystwyth University, and Wetlands International. Financed by the European Space Agency (ESA), the project objective was to develop a system that provides monthly mangrove forest change alerts to support end users in mangrove protection, conservation, restoration, and management. The RAMM system aimed to complement an existing optical image detection system implemented by Global Mangrove Watch (GMW) to inform local governments about change in their mangrove ecosystems.

This Final Report provides a description of all the work done during the RAMM project and introduces the context, the activities performed, and the main results achieved.

2.0 CONTEXT

Mangroves provide a suite of nature-based solutions; they protect coastlines from sea-level rise and erosion, can be a biodiversity hub, capture large amounts of carbon, and can be an important part of local communities' livelihoods[1]. These important ecosystems are under threat, due to developments such as aquaculture, plantations, or over exploitation for wood[1].

GMW is an online portal that provides global updated annual baseline mangrove extent using ALOS PALSAR (-1 and -2), Landsat and more recently Sentinel-2 (S-2) data [1], [2]. The Department of Geography and Earth Sciences, Aberystwyth University (DGES) is a technical lead for GMW product development and collaborates with members of the Global Mangrove Alliance (GMA)[1], an unprecedented collaboration that brings together more than 40 non-governmental organizations (NGOs), governments, scientists, industry, local communities, and funders towards a common goal of conserving and restoring mangrove ecosystems. Wetlands International is one of five international NGOs coordinating the GMA and works closely with DGES to deliver the current GMW products.

The GMW Portal annual maps are important for historical mangrove extent accounting, but the ongoing protection of mangroves and interventions to prevent and minimize losses requires more timely alerts of mangrove loss. Since February 2023 the GMW portal has provided a monthly alert system for about half of the world's mangroves [3] based on the analysis of S-2 imagery on a monthly basis. This system has demonstrated the importance of providing timely information to stakeholders but is limited in some regions due to cloud cover resulting in a typical lag time of 3 months between a disturbance occurring and being confirmed by the system and posted on the GMW portal. Additionally, in some regions a high number of false positives due to changes in water level has been identified which has resulted in an additional delay between analysis and alerts being posted on GMW portal to allow the alerts to be quality assured and false positives removed.

The RAMM project addressed the requirements of GMA members for a mangrove change alert system that is integrated with the GMW Portal and can provide GMA members and a broad user community with timely monthly alerts. To achieve this, the objective was to exploit the full Sentinel-1 (S-1) time series and build a RAMM system for automated monthly detection of mangrove loss complimentary to the S-2 system.

[1] https://www.mangrovealliance.org/

3.0 CONCEPT OF RAMM ALGORITHM & SYSTEM

The RAMM system concept of operations is to detect and report monthly mangrove loss using S-1 data. The domain is the GMW v4.0 baseline for 2020 (Bunting et al., 2024). To ensure acceptable processing speed and cost, the RAMM system is hosted in the Copernicus Data Access System (C-DAS) and uses Kubernetes and Dask, which are among the latest approaches for cloud-optimized scalable computing. Using open geospatial Python packages and libraries, the RAMM system can automatically process newly acquired S-1 data and deliver change alerts, which can be integrated into the GMW Portal.

4.0 RAMM SYSTEM DEVELOPMENT

The technical objectives for the development of the RAMM system were:

1. Benchmark candidate change detection algorithms using S-1 time series data for monthly mangrove change alerts.

2. Implement the best performing algorithm in the C-DAS using open, cloud-native standards to enable scalability of the RAMM system to global alerts.

3. Validate the performance of the RAMM system using a GMW validation dataset and evaluate the impact with end-users.

4. Develop a roadmap for operating RAMM across priority mangrove ecosystems globally.

4.1 BENCHMARKING

Benchmarking of four candidate algorithms/approaches for change detection using S-1 time series data was undertaken and reported in Deliverable D1 (Technical note on the algorithm benchmarking results). Four algorithms/approaches were assessed:

1. **Lightweight decision tree** based on the establishment of thresholding values, to identify based on the establishment of thresholding values, to identify pixels that have undergone canopy loss.

2. **Single pixel timeseries deep learning analysis** using a single dimension data layout to represent state over time will be used as model input and resulting in “changed” and “non-changed” classification; essentially detecting the anomalous divergence of mangrove health state.

3. **Spatial deep learning approach** using a U-Net framework to fuse the information from Sentinel-2 and complimenting with the additional information encoded in Sentinel-1 data. Leveraging multi-modal informatic sources to provide outputs of change detection between two sequentially temporal state.

4. **Probabilistic change method** based on calculating mangrove forest and non-forest probabilities for each pixel for each S1 observation compared to a time series of radar polarization metrics for stable mangrove forest.

The results of the algorithm benchmarking showed that each method had its own strengths and limitations in detecting mangrove deforestation using Sentinel-1 time series data:

- The lightweight decision tree method was simple and fast, but it tended to over-predict deforestation and missed some subtle changes.
- The 1D-CNN method was able to learn complex patterns from the time series and achieved high accuracy, but it required more computational resources, as compared to the decision tree, and data preprocessing.
- The 2D-CNN method was able to incorporate spatial context and temporal information, but it faced challenges in distinguishing mangrove deforestation from other changes, and it needed a larger and more balanced dataset.
- The probabilistic change method, based on the RADD algorithm, was not directly tested, but it was expected to be robust and efficient for canopy disturbance detection in stable forest, although it would require adaptations and intensive data preprocessing to account for the dynamics of mangroves and the influence of inundation and rainfall.

With respect to the data itself, when analysed as a timeseries of backscatter values and understanding the challenge of relating labeled datapoints from optical to radar, patterns emerged that indicated the potential for identifying change alerts earlier than the optical workflow. Based on the findings, a **two-stage algorithm** was selected as the most suitable and feasible solution for the RAMM system in this project.

The two-stage approach consists of:

1. Applying a **lightweight decision tree** method as the first stage, which uses an eager threshold to over-predict change alerts, i.e., it has a high recall but low precision.
2. Applying a **1D-CNN** method, which takes the output of the first stage and validates or rejects the predicted change alerts, i.e., it has a high precision but low recall.

The combination of these two stages aimed to achieve a high overall accuracy and robustness while reducing the computational complexity and memory requirements of the system. The two stage algorithm approach was defined in Deliverable D2 (Algorithm Theoretical Basis Document.)

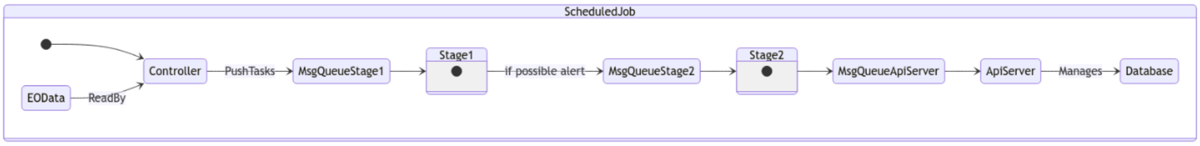
4.2 IMPLEMENTATION

The RAMM system was deployed in Kubernetes inside of the CloudFerro infrastructure of C-DAS. The system consists of two distinct operational components of RAMM (Figure 1):

- API server – a restful agent validating requests for both the reading and the updating/insertion of data.
- Analysis workflow – the flow of operations when the scheduled/submitted job is run.

A job controller is created by the scheduled/submitted job and this entity manages the operation to completion, handling any errors/failures appropriately that may occur. Workers are created in response to an event on the message queue that it is listening to. If, in Stage 1, a possible mangrove loss alert is identified by the eager lightweight decision tree then it is subsequently inserted into the Stage 2 message queue. Stage 2 Workers react in the same way as Stage 1 but only on a subset of data, as it is likely that not all pixels will be possible mangrove loss alerts. When the queue is empty and the workers cannot pull any more tasks, then they will self-terminate/scale-down.

Figure 1 RAMM System overview.



Using an event-driven workflow, RAMM can dynamically process an abundance of tasks with each task being a unit of area with respect to the mangrove extent. Assigning area in a task allows for a given Worker to process more than a single point at a given time, utilising its physical resources. The workflow and cloud system were defined in detail in Deliverable D3 (Technical note on specification of the Cloud Platform Environment) and Deliverable D4 (Technical note on verification of system performance for demonstration period).

During implementation, the RAMM system was configured to accept several parameters that could be set and tested to optimize the omission and commission errors for detection of mangrove loss. The parameters were:

- Stage 1 score – the number of sequential detections required meeting stage 1 algorithm requirements for a detection to be passed to stage 2. The testing involved the requirement for 3 or 4 sequential stage 1 detections.
- Stage 2 threshold – the threshold required to classify an alert based on the probability output of the Stage 2 CNN model. The testing involved a probability threshold of 0.5 or 0.8.
- GMW v4.0 baseline erosion – the number of 10 m pixels used as the basis to internally erode the GMW baseline, which removes any mangrove loss alerts from edge areas of the mangrove extent. The testing involved erosion of 1, 2, or 3 10 m pixels.

4.3 VALIDATION

Validation of the performance of the RAMM system was challenging due to complex and time-consuming process to develop independent reference data. The approach was split into two parts to answer the following questions [3]:

1. Does the RAMM system capture the mangrove losses that have occurred within the monitoring period?
2. Does the RAMM system capture the timing of the mangrove loss events?

For the first component, the accuracy of the mangrove loss alerts was assessed using a 130-m hexagonal grid. All the hexagons intersecting the GMW v4.0 baseline (Bunting et al., 2024) for 2020 were selected. This is the same mangrove extent baseline used for the RAMM alert system. A random sample of 2600 was then taken, representing a total area of approximately 3,654 hectares. The 130 m grid cells were visually evaluated to determine if mangrove loss had occurred using high-resolution Planet satellite monthly mosaics. For each hexagon, it was first checked as to whether the hexagon included mangroves in 2020 and, secondly, whether some or all the area of mangroves had been lost by February 2025. Therefore, the full period over which the RAMM mangrove loss alerts have been generated was considered. Additionally, errors due to the incorrect allocation of mangroves within the GMW v4.0 baseline (Bunting et al., 2024) were also considered, allowing the whole system's accuracy to be considered. Hexagons where there was a very small overlap with the GMW mangrove extent mask and verified using the planet imagery were removed from the analysis, and this left a total of 2550 hexagons to be used for the accuracy assessment. A bootstrapping approach (Bunting et al., 2023) was used to estimate the accuracy metrics and 95% confidence interval for those metrics. The bootstrapping used a 40% sample without replacement and 1000 iterations.

For the second part of the accuracy assessment, a sample of 100 RAMM mangrove loss alerts were selected and using the monthly planet composites the month where the change was first observed in the Planet composites was allocated to each point. The difference between the month of the observed change and the date of the alert date were then compared to understand the ability of the RAMM system to identify the mangrove losses in a timely manner. It should be noted that there is a difference in modality between the S-1 data used for the alerts and the Planet imagery used to generate the reference change dates. Therefore, cases of canopy dieback might be observed within the Planet imagery but not the S-1.

RAMM System Performance to Capture Mangrove Loss

The requirements of an operational system need to be considered to identify the best overall system. As the alerts are made available through the GMW online portal and are expected to be used visually, the requirement is to direct users to areas of loss rather than to capture the full extent of any given losses. Ideally, both the omission and commission rates would be low. However, to allow the system to be operationalised, it is more important to minimise the number of commission errors to avoid false alerts. Therefore, we would accept a higher level of omission to avoid a high commission level.

With these requirements in mind, the optimal configuration of RAMM was a score of 3 in Stage 1, a threshold of 0.8 in Stage 2, and 1 pixel of erosion applied to the GMW v4.0 baseline.

Figure 2 provides an example of RAMM system mangrove loss detection with Planet images shown before the mangrove loss and afterwards. Panel a and b illustrate an example of a small track that the system has not identified. Panel c and d illustrate an area where mangrove loss was detected, however, the full extent of the mangrove losses have not been identified. Panel e and f illustrate an example of a subtle mangrove loss which occurred at the end of 2024, which the system had not yet captured.

Figure 3 provides an example of mangrove loss detection in Stage 1, prior to Stage 2 and prior to the GMW baseline erosion process. An area of mangrove loss is detected (red box), but the coastline includes numerous detections that are errors of commission related to edge effects. Most of these commission errors are removed through the GMW baseline 1 pixel erosion.

Figure 2 Example of RAMM system identification of mangrove loss, with omission cases.

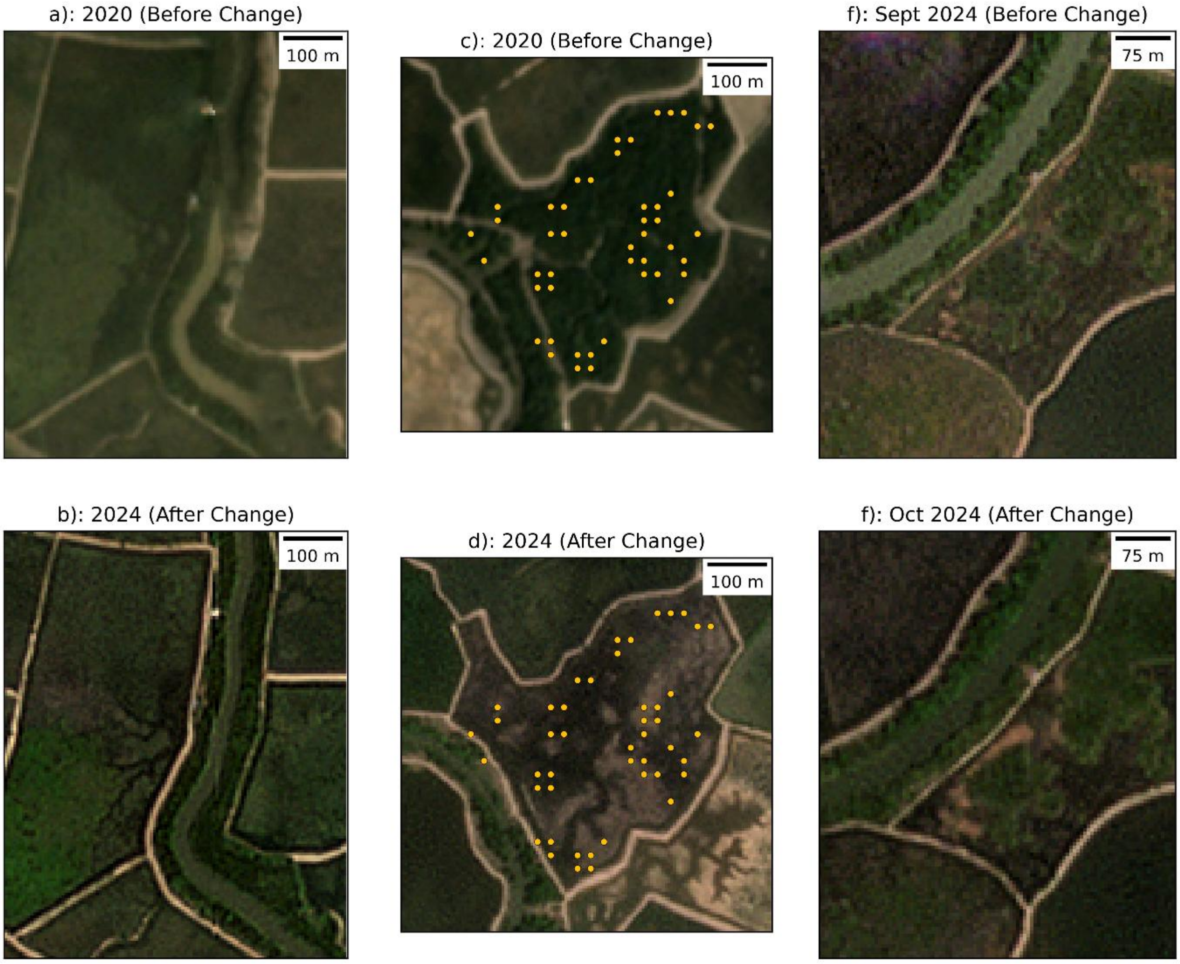
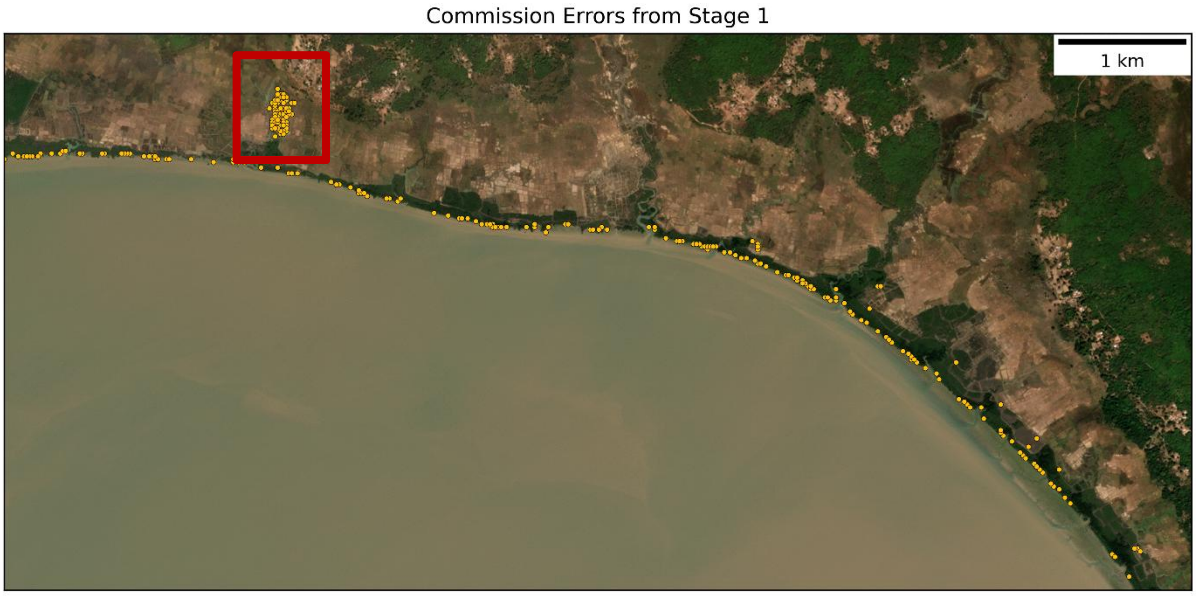


Figure 3 Example of RAMM system identification of mangrove loss (red box), with stage 1 commission cases along coastline.



This parameterisation results in a low commission of 5.1 % and an omission of 37.0 %. While the omission rate is higher than would be ideal for the GMW mangrove loss alert system, from a visual inspection, most mangrove loss regions have at least one point associated with them, and therefore, these areas of loss would be identified to end users even though the full extent would not be captured.

RAMM System Performance to Capture the Timing of the Mangrove Loss Events

The RAMM system was configured to attribute mangrove loss alert points with two associated dates: the first date is the first time a pixel was observed as a change within Stage 1, and the second date is when the pixel reaches the Stage 1 score threshold (i.e., 3) and therefore Stage 2 confirmed the change.

Once a change has been first identified, the average time taken to confirm a change is 30 days, which is well suited to a deforestation alert system. However, the median difference between the change occurring and being first detected by the RAMM system is 366 days, with an upper quartile (i.e., 75 % of the alerts) of 585 days. Therefore, it took over a year for most of the alerts to be identified and confirmed by the RAMM alert system; this is beyond the period expected.

Figure 4 provides a comparison of the Sentinel-1 and Planet imagery, where the change can be seen to occur between August and September 2022 within Planet imagery. However, there is little change in the magnitude of the Sentinel-1 backscatter, with the change becoming more apparent about 12 months after the change is observed within the Planet imagery (Figure 5). Unfortunately, this breaks the assumption on which both Stages 1 and 2 of the RAMM alert system were built and illustrates why the RAMM system can identify the loss alerts but fails to recognise them within a short time window.

Figure 4 a) monthly Planet composites showing mangrove loss between Aug-Sep 2022. Orange circle indicates location of RAMM alert. b) S-1 timeseries (VV, VH NDPI) for the same months.

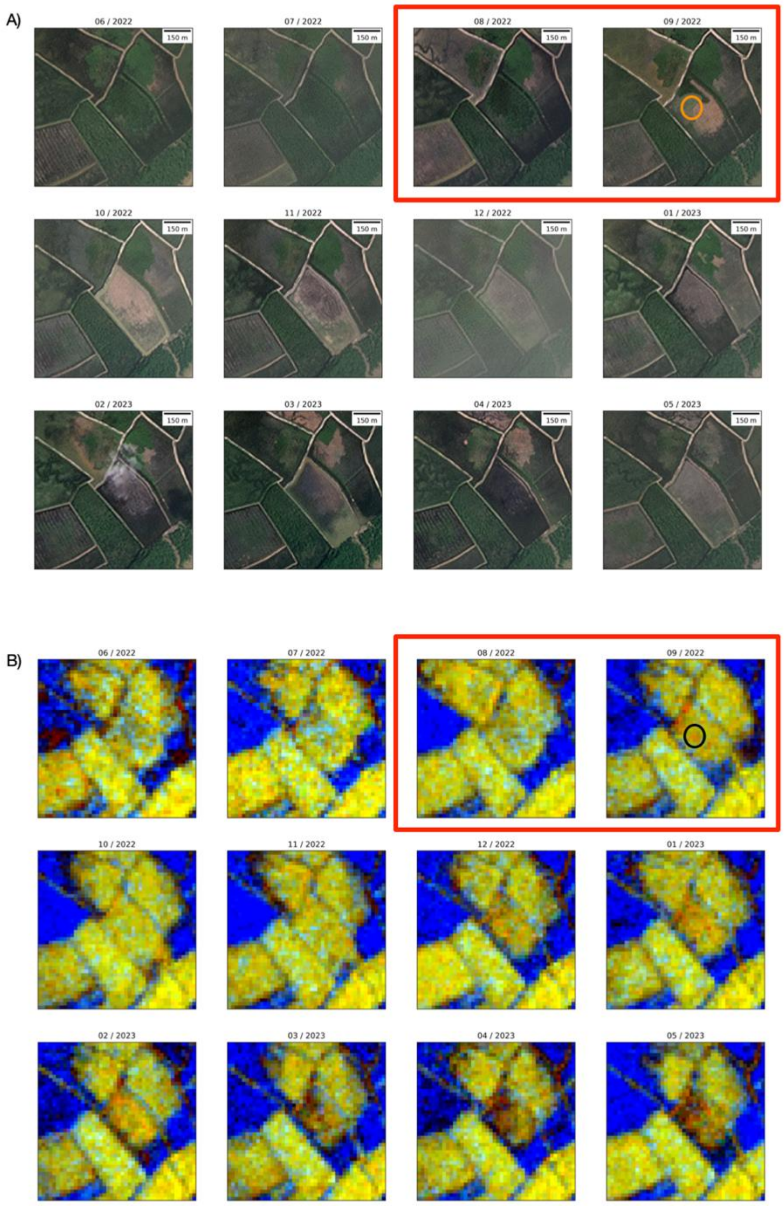
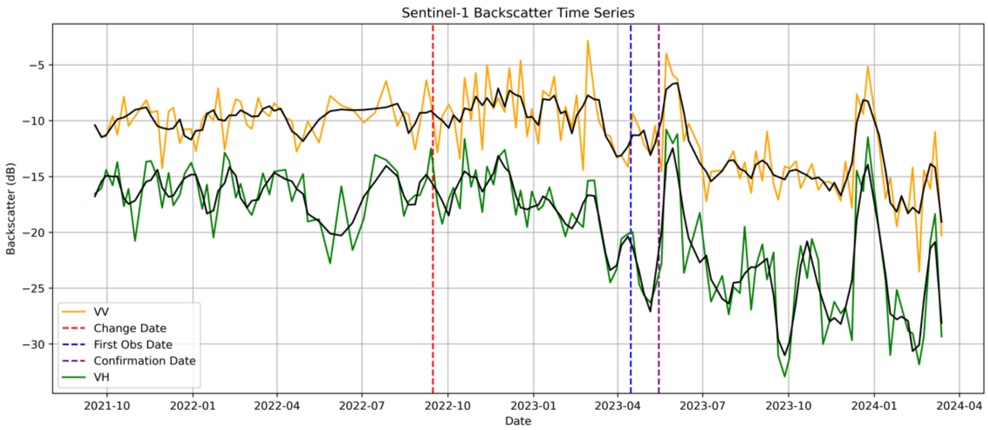


Figure 5 S-1 backscatter 09/2021to 04/2024, which illustrates that at the observed change date (09/2022), there change in the magnitude of the S-1 backscatter values takes 12 months.



4.4 EVALUATION & ROADMAP

The RAMM mangrove loss alert system demonstrated that it reached the design goal of identifying mangrove losses with a low commission error of approximately 5 %. Although the omission rate is relatively high at 37 %, this is primarily due to missing the full extent of the mangrove loss areas rather than missing the loss regions entirely. Given that end users are expected to be using these alerts as a visual product to direct them to regions of change this is an acceptable compromise.

The ability of the RAMM system to identify the alerts in a timely manner is more limited. In this case, 25 % of the alerts were identified within 242 days, 50 % within 395 and 75 % within 617 days of a change being first observed within the Planet monthly composites. This compares unfavourably with the GMW Mangrove Loss alert system using S-2 (Bunting et al., 2023), where 75 % of the alerts were identified within 90 days of the change being identified with the Planet monthly composites. To move forward with S-1 for mangrove monitoring, more work is needed to understand the backscatter response within these ecosystems and how the S-1 signal responds to changes in the mangrove canopy and structure.

A Roadmap defines the proposed actions to improve the performance of the RAMM system and to address user requirements for a timely and accurate global mangrove change monitoring system. The key features of the Roadmap are:

1. Adopt RAMM innovations as part of the existing Sentinel-2 mangrove change alerts system:
    - Implement two-stage event-based pipeline
    - Implement a 1D-CNN or 2D-CNN for Stage 2 to reduce the number of false positives and efficiency of quality assurance
2. Research to develop multi-SAR sensor mangrove alerts:
    - Research into performance of C-band SAR for detection of change for different mangrove types, typologies, changes (degradation, loss), etc
    - Testing the performance of NISAR and BIOMASS data
    - Advance the concept of the Multi-sensor Alerts for Mangrove Monitoring (MAMM)

The evaluation with GMA members involved Wetlands International demonstrating the system to staff of their offices in Guinea-Bissau and Indonesia followed by discussion of the impact of the RAMM system for mangrove monitoring, conservation, and management. This confirmed that the RAMM system would enhance information for on-the-ground conservation action if the RAMM system is used to improve the Sentinel-2 based alerts, or if the proposed Roadmap is implemented.

5.0 CONCLUSIONS AND NEXT STEPS

The RAMM project developed a system that utilized S-1 data to produce monthly mangrove forest change alerts. The objective was to complement the existing S-2 detection system implemented by GMW. The RAMM system was established in the European C-DAS cloud infrastructure and uses Kubernetes and Dask to ensure efficient, scalable computing.

The RAMM workflow is intended to ensure computational efficiency. Analysis is completed only within the domain of the GMW v4.0 baseline mangrove extent. For mangrove change detection, a **lightweight decision tree** method is implemented first followed by a **1D-CNN** deep learning method. The RAMM system can be scheduled or triggered by the user to automatically process the workflow. A simple web portal was established for launching and managing jobs.

The RAMM system met GMW's technical objectives and met seven of the eight requirements (see Table 1). A summary of the outputs from the project is provided in Table 2. The key issue is the timeliness of the mangrove loss detections with S-1.

A review of the RAMM system by GMW and with GMA members supported the development of a Roadmap, which defines the foundation for enhancements that will yield the most significant positive impact for GMA and its members.

Table 1 Review of RAMM project objectives and requirements.

Overall objective is a RAMM system that provides monthly mangrove forest change alerts to support end users in mangrove protection, conservation, restoration, and management		
REQ-1	Monthly alerts of mangrove loss. Target better than 90% overall accuracy. Point format to match the current GMW optical alerts format and evaluate delivery in a polygon format with 0.1 ha MMU.	**Assessment – partially achieved** ▪ Monthly alerts produced in point format ▪ Independent accuracy assessment showed acceptable accuracy ▪ Timeless of detection of change identified as critical issue
Objective 1 Benchmark candidate algorithms for change detection using Sentinel-1 time series data for monthly mangrove change alerts.		
REQ-2	Project shall benchmark **4 methods / algorithms** based on a) Accuracy, b) ability for monthly alert consolidation, c) Speed; and d) Processing resources, including optimization of processing (number of workers, chunk size, etc.)	**Assessment – achieved** ▪ Benchmarking results included 1-D and 2-D CNN methods. ▪ Benchmarking supports GMW roadmap to investigate 2-CNN for RAMM system

REQ-3	Algorithm Theoretical Basis Documents (ATBD) for the selected algorithm adhering to the Findable, Accessible, Interoperable, Reproducible (FAIR) principles	**Assessment – achieved** ▪ ATBD document publicly available on
Objective 2 Implement the RAMM system using the selected algorithm in the C-DAS using open, cloud-native standards to enable scalability to global alerts		
REQ-4	RAMM system implementation shall leverage cutting edge cloud computing	**Assessment - achieved** ▪ Algorithm implemented in C-DAS. ▪ Products delivered as cloud-native datasets suitable for integration into GMW Portal.
REQ-5	Algorithm published under FAIR principles	**Assessment – partially achieved** ▪ Algorithm will be published on GMW Github page
Objective 3 Validate the performance of the RAMM system using a GMW validation dataset.		
REQ-6	Two large scale demonstrations, at least one in Africa and country scale	**Assessment - achieved** ▪ Pilot site in Guinea Bisau (country scale) ▪ Pilot site in North Kalimantan, Indonesia ▪ Duration of alerts over four years
Objective 4 Develop a roadmap for evolution of RAMM and operating across mangrove ecosystems globally		
REQ-7	Roadmap identifying a) the remaining challenges and gaps relative to mangroves monitoring using Sentinel-1 data; b) R&D agenda to tackle those challenges; c) all necessary steps to further evolve the RAMM system and methods to scale-up to a global scale.	**Assessment - achieved** ▪ Roadmap document
REQ-8	Champion User and Early Adopters shall be engaged in the project and co-develop the roadmap for RAMM evolution	**Assessment - achieved** ▪ Assessment of RAMM system with GMA members

Table 2 Summary of deliverables.

Deliverable	Content	Status/
D1	Technical Note of algorithm benchmarking results.	Delivered
D2	ATBD	Delivered
D3 & D4	Technical Note on specification of the cloud platform environment Technical Note on verification of system performance for demonstration period.	Delivered
D5	Validation Report of RAMM monthly alerts	Delivered
D6 & D7	Evaluation of RAMM system and its impact with GMA members Roadmap	Delivered
D8	Open access publication manuscript	Delivered
TDP	Technical Data Package	Stage 1 and Stage 2 algorithm code submitted to GMW GitHub site
FR	Final Report	Delivered (this document)
CCD	Contract Closure Documentation	
FP	Final Presentation	

6.0 REFERENCES

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[2] P. Bunting *et al.*, "The Global Mangrove Watch—A New 2010 Global Baseline of Mangrove Extent," *Remote Sens.*, vol. 10, no. 10, p. 1669, Oct. 2018, doi: 10.3390/rs10101669.

[3] P. Bunting *et al.*, "Global Mangrove Watch: Monthly Alerts of Mangrove Loss for Africa," *Remote Sens.*, vol. 15, no. 8, p. 2050, Apr. 2023, doi: 10.3390/rs15082050.