Geospatial Optimization of Surveillance Tower Deployment for Maritime Coverage in the Aegean Sea

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Abstract

This study addresses the optimization of surveillance tower placement across the Aegean Sea to maximize the detection of small-scale maritime vessels (9-meter rib boats). We propose a constraint-based deployment strategy utilizing a binary sensor model with ranges of 7 km and 14 km, capped at a maximum of 1,000 units. By processing satellite imagery from the USGS database into a binary land-sea matrix, we implemented a heuristic coastline segmentation algorithm to determine optimal tower coordinates. The resulting configuration achieved a coverage of approximately 20% of the Aegean Sea ($80,871$ km^2) utilizing 579 towers. This paper discusses the algorithmic approach, coverage efficiency, and proposes future pathways utilizing Mixed-Integer Programming (MIP) for topographic refinement.

1 Introduction

The monitoring of maritime activity in the Aegean Sea presents a complex geospatial coverage problem. The primary objective of this project is to identify optimal land-based locations on islets and coastlines to maximize the surveillance area for detecting 9-meter rib boats.

The constraints allow for the deployment of up to 1,000 surveillance towers. Two sensor variations are available: a short-range variation (7 km) and a long-range variation (14 km). The optimization problem seeks to maximize the total sea surface area covered (A_{total}) while prioritizing the minimization of tower count and the efficient use of short-range sensors where long-range overlap is excessive.

2 Problem Analysis and Assumptions

The problem is modeled as a Maximum Covering Location Problem (MCLP) applied to a discretized grid. The following assumptions govern the simulation:

- **Binary Detection:** A sensor successfully detects a vessel if the vessel lies within the Euclidean distance of the sensor's specified radius ($R \in \{7, 14\}$).
- **Placement Constraints:** Towers are restricted to island coordinate sets; mainland locations are excluded from the solution space.
- **Geospatial Simplification:** Earth curvature is considered negligible for the pixel-to-kilometer conversion, where one degree of latitude is approximated as 111 km.
- **Topography:** Elevation data is omitted in this iteration to focus on 2D planar coverage.

3 Methodology

3.1 Data Preprocessing and Segmentation

The simulation environment was constructed using Global NDVI maps in TIF format, sourced from the USGS MODIS satellite database. The global map was cropped to the specific longitude and latitude of the Aegean region.

To isolate valid deployment zones, the map was converted into a binary matrix $M_{i,j}$ where 1 represents land and 0 represents sea. Mainland clusters were algorithmically erased to strictly target island coastlines for deployment.

(a) Global NDVI Map (Source: USGS)

(b) Cropped Binary Study Area

Figure 1: Preprocessing of satellite imagery to isolate the Aegean Sea region.

3.2 Heuristic Coastline Optimization Algorithm

While optimal coverage problems are often solved using Integer Linear Programming, the scale of the Aegean grid necessitates a computationally efficient heuristic approach for this initial iteration. We developed a *Variable-Range Coastline Segmentation* algorithm:

1. **Long-Segment Traversal ($L_s > 14$ km):** For extended coastlines, 14 km range towers are deployed at 14 km intervals ($d = 14$). This minimizes the number of nodes required to cover large perimeters.

2. **Short-Segment Optimization ($L_s < 14$ km):**

   - By default, a 14 km tower is placed to maximize the radial coverage extending into the sea surrounding small islets.
   - **Overlap Reduction:** To mitigate redundancy in dense archipelagos (e.g., the Cyclades), the algorithm interleaves 7 km sensors. Specifically, for every second tower placed on islands with spacing exceeding 7 km, the sensor range is downgraded to 7 km.

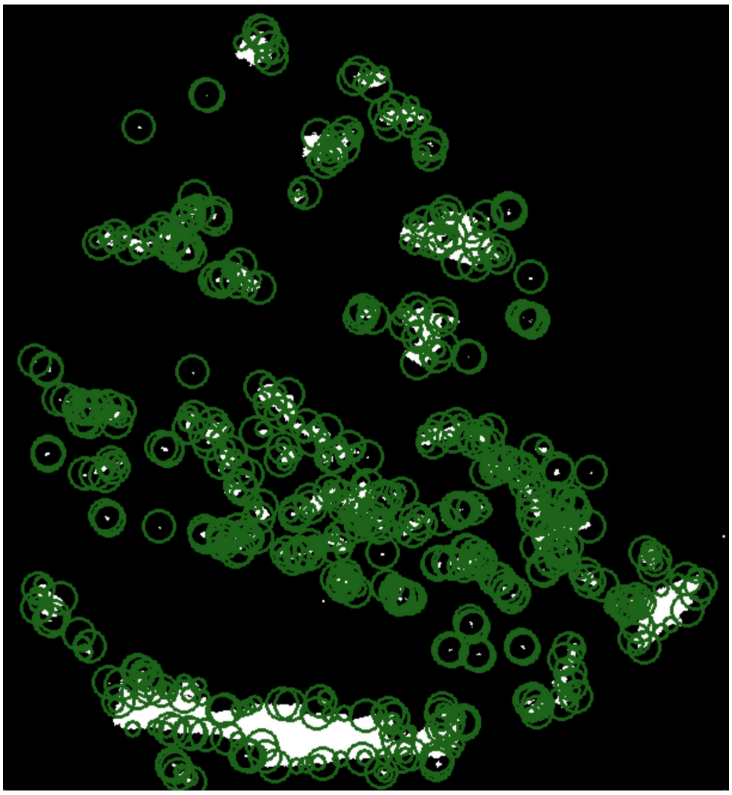
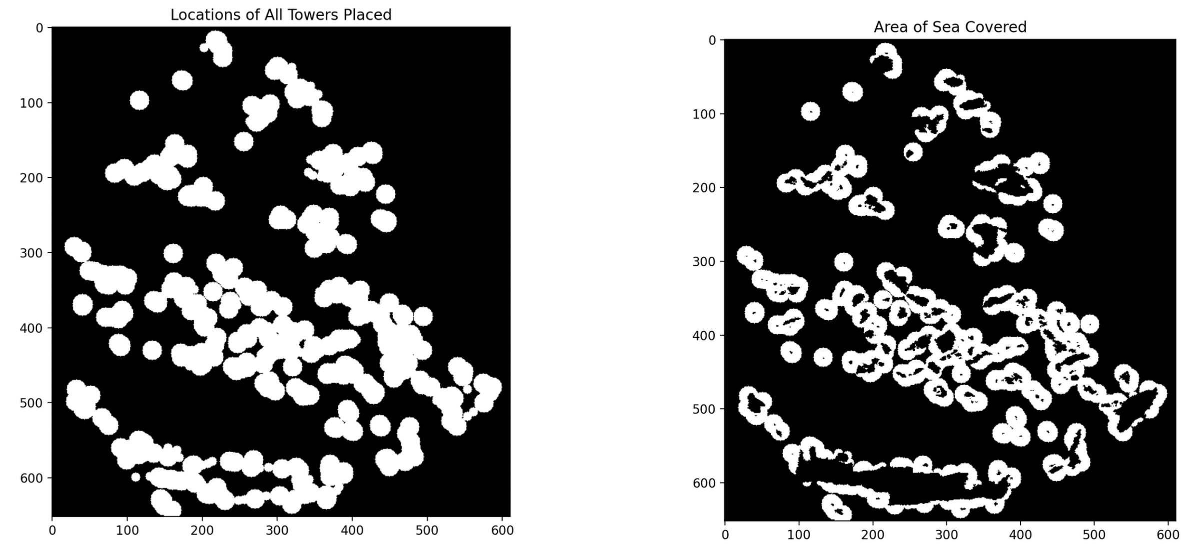


Figure 2: Resulting tower distribution. Green circles indicate sensor range radii centered on island coordinates.

4 Experimental Results

The algorithm generated a deployment map coordinates and sensor types for all deployed units.



(a) Locations of All Towers Placed

(b) Area of Sea Covered

Figure 3: Binary masks representing the distinct tower locations (left) and the cumulative sensor coverage area (right).

As shown in Table 1, the solution utilized significantly fewer than the maximum 1,000 towers, suggesting high efficiency in resource usage.

Table 1: Deployment Statistics and Coverage Metrics

Metric	**Value**
Total Towers Deployed	579
Total Sea Area Covered	80,871.04 km^2
Percentage of Aegean Covered	$\approx$ 20%
High-Range Towers (14 km)	400
Low-Range Towers (7 km)	247

```
Covered 0.20pct of Aegean, for a total of 80871.04 km^2
Total Towers Used 579.00
Range
13.053053    400
6.526527     247
Name: count, dtype: int64
        Key  Latitude  Longitude      Range
0  Island_4      17.0      217.0  13.053053
1  Island_4      18.0      220.0  13.053053
2  Island_5      21.0      210.0   6.526527
3  Island_5      23.0      221.0  13.053053
4  Island_5      27.0      202.0   6.526527
```

Figure 4: Terminal output showing data frame statistics and coordinate logs for the first five deployed units.

5 Discussion

The implementation of the coastline segmentation heuristic provides a functional baseline for maritime surveillance, yet analysis reveals distinct inefficiencies inherent to the current indexing logic.

5.1 Coverage Gaps and Algorithmic Limitations

Visual inspection of the deployment map (Figure 2) highlights a critical coverage failure on the Southwest coast of the large northern island. This gap indicates a flaw in the pixel indexing or traversal order of the algorithm. The algorithm likely treats the coastline as a discontinuous array of points, potentially skipping segments that do not align perfectly with the 14 km or 7 km stride intervals. This suggests that a continuous-path tracing algorithm would offer superior robustness compared to the current interval-based logic.

5.2 Resource Allocation and Overlap

While the goal of using fewer towers was met (using only 579 of the allocated 1,000), the distribution reveals significant sensor overlap, particularly in the Cycladic region. The current model's rudimentary interleaving of 7 km towers is insufficient for complex archipelagos. This overlap represents an economic inefficiency. In a real-world scenario, the operational cost of a 14 km tower is likely significantly higher than that of a 7 km tower. Therefore, the current "surplus" of 14 km towers (400 units vs. 247 short-range units) may maximize range but fails to optimize the cost-to-coverage ratio.

5.3 Topographic Blind Spots

The current solution relies on a binary land/sea assumption. By neglecting elevation data, the simulation assumes infinite line-of-sight. In reality, the rugged topography of Aegean islets would significantly occlude sensors. A 14 km range is theoretical; actual coverage would be severely limited by island ridges, necessitating a viewshed analysis that the current 2D model cannot provide.

6 Conclusion and Future Work

This project established a foundational framework for maritime surveillance optimization in the Aegean Sea. By converting raw satellite data into a binary deployment grid and applying a variable-range heuristic, we achieved 20% coverage of the total sea area using only 57.9% of the available tower budget.

However, the analysis confirms that a simple heuristic approach faces limitations regarding coverage continuity and economic optimization. To resolve the specific questions regarding the preference for 7 km vs. 14 km towers, future iterations must move beyond simple geometry to mathematical programming:

- **Integer Linear Programming (ILP):** Formulating the problem as an ILP would allow for the rigorous application of cost functions. This would mathematically weigh the benefit of a 14 km tower against its cost, naturally selecting 7 km towers in dense clusters where overlap renders long-range sensors redundant.
- **Mixed-Integer Programming (MIP) for Topography:** To address the lack of elevation data, future work should integrate OpenStreetMaps via the OSMnx Python package. This allows for the inclusion of real-world topography, converting the problem into a Mixed-Integer Programming task where "visibility" is a calculated variable rather than an assumed constant.

Ultimately, while the current draft successfully demonstrates the feasibility of automated placement, the transition to ILP/MIP frameworks is essential to achieve a truly optimal, cost-effective, and geologically accurate surveillance network.