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A Multi-Band, Multi-Mission Phased Array Network in the CONUS

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1. INTRODUCTION

Numerous studies have proposed a next-generation Multi-Mission Phased Array Radar (MPAR) network in the United States, however most of these have focused on either the S-band or the X-band exclusively. Since the multi-mission piece of the MPAR project is of high importance, a single-band network would be problematic in providing a replacement for the four main radar networks in the CONUS (WSR-88D, Terminal Doppler Weather Radar, Airport Surveillance Radar, and the Air Route Surveillance Radar). A multi-band network could provide the capability to manage the multiple radar missions in the CONUS while still offering a cohesive, joint-effort MPAR network with similar designs, centralized maintenance and support, and significantly increased coverage and performance. A sample comparison of differing band options will be presented for a limited domain in order to demonstrate capabilities to maximize coverage while minimizing complexity.

2. PURPOSE AND MOTIVATION

The current generation of WSR-88D radar systems are now more than 20 years old (Yussouf and Stensrud 2008), leading researchers to begin exploring options for the next long-range weather surveillance network in the United States. Of principle interest is decreasing the time needed to complete a full volume scan in order to provide forecasters with more time and data for issuing warnings (Brown et al. 2009). This goal can be attained by using electronically-steered phased array technology, and is currently being used for weather observations in Norman, Oklahoma at the National Weather Radar Testbed (Heinselman et al. 2008).

Equally as interesting, however, is the ability for the Multi-Mission Phased Array Radar (MPAR) to perform multiple scanning tasks simultaneously. This possibility has led to the proposal of combining multiple radar networks into a new long-range weather surveillance network (Weber et al. 2007). In doing so, the potential exists to reduce costs and complexity by having one radar network for four missions managed by one central agency with one central maintenance source.

a. *Current Networks*

The four radar networks which Weber et al. (2007) proposes to be combined consist of over 500 radar systems collectively, many of which overlap significantly in coverage. Despite this high number of systems, however, large areas (especially at low levels) remain uncovered by a weather radar site. The Terminal Doppler Weather Radar (TDWR) network consists of 45 C-band weather radars, powered by a 230 kW Klystron transmitter. These radars are placed at major airports around the United States, and specialize in airport-area mesoscale weather observations (specifically downburst and turbulence detection). TDWR systems have a reflectivity range of 460 km and a Doppler range of 90 km.

The Aircraft Surveillance Radar (ASR) network is also used at major airports, and provides aircraft tracking at short- to medium-range for congested areas. This system features an S-band 20 kW solid-state transmitter, and has a tracking range of approximately 111 km (ASR-11; older systems have different specifications). The Air Route Surveillance Radar (ARSR) network is a longer range system designed for aircraft tracking across the entire United States. The ARSR-4 consists of an L-band 60 kW solid-state transmitter, and can provide aircraft tracking up to 460 km in range (older ARSR systems have different specifications).

The Weather Surveillance Radar 88 Doppler (WSR-88D) network is used primarily for weather surveillance by the National Weather Service (NWS), but is also used by the Federal Aviation Administration (FAA) and a host of other government agencies. The system features an S-band, 750 kW Klystron-based transmitter, and has a reflectivity range of 460 km and a Doppler range of 115

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km. The S-band frequency allows fairly long-range observations; the cost of this large areal coverage, however, is a distinct lack of low-level coverage at long ranges from the radar site.

b. *Proposed Networks*

Two different networks have been proposed for a next-generation weather radar network, each offering significant advantages over current networks. As previously mentioned, an MPAR network would be capable of providing observational services to multiple missions, reducing the need for multiple networks with different specifications, organizations, and maintenance services. This method would ideally reduce costs in many ways, including construction, operation, and maintenance. The cost of large, S-band phased array radars, however, is estimated to be relatively substantial.

In order to alleviate individual radar costs, as well as mitigate low-level coverage problems, the Collaborative Adaptive Sensing of the Atmosphere (CASA) program proposes a network of low-cost, low-power X-band radars that is capable of adaptively sensing the atmosphere at low levels (Brotzge et al. 2006). CASA is currently operating a testbed of mechanically steered radars in central Oklahoma, however its radars will be phased array systems in the near future. CASA is capable of adapting radar scanning strategies in order to “follow” storm cells which are targeted by the forecaster/operator, providing faster updates and more radars offering low-level coverage of important severe weather events.

c. *Motivation and Goals*

The use of just one of the above methods would limit a next-generation multi-mission radar network in the United States to just one band (either S-band or X-band). Current radar networks that will need to be replaced range from C-band to L-band (5 cm to 30 cm wavelengths), and they exist at these bands for specific reasons. The ARSR system operates at L-band to facilitate very long-range tracking capabilities, while the TDWR mission of downburst detection benefits from operating at C-band. For this reason, we propose the exploration of a multi-band network of phased array radar systems for use in the United States.

A multi-band network (currently S-band and C-band or S-band and X-band combinations are being explored) would offer more potential for ideal attainment of the goals of all four current radar networks. We propose that long-range aircraft tracking and weather surveillance (ARSR and WSR-88D) could be achieved using S-band systems, while short-range aircraft tracking and weather surveillance (ASR and TDWR) could be achieved using the higher-frequency system (C- or X-band). Additionally, by combining bands, the adaptive technologies employed by CASA could potentially be used as well.

The combination of two frequencies would provide significant improvements in low-level coverage, while minimizing cost (via more expensive S-band systems and lesser expensive C-/X-band systems). A secondary advantage, however, would be a centralized oversight and maintenance organization; by using similar designs and parts, the four current radar networks could be combined into one network with only two designs which would need to be maintained. It is thought that this could also conceivably lower overall network costs and complexity.

3. METHOD

The goal of this research is intended to minimize cost while maximizing areal coverage of a dual-frequency MPAR network in the continental United States. In doing so, all missions can be achieved, while also allowing for potential adaptive scanning techniques and significantly better low-level coverage compared with current national networks. The problem can be thought of as an optimization problem with a cost function that is to be minimized computationally. There are a number of optimization methods available, with varying advantages and limitations. Since this is a real-world, 3-dimensional problem, we must be able to use realistic boundaries in a non-linear sense. Additionally, it is important to consider computational power/speed, as well as customization options within the software platform. By weighing these options, it was determined that a genetic algorithm would be most advantageous in solving our problem (Deb et al. 2000).

The focus of this paper is to provide an initial analysis of how the genetic algorithm is being utilized at this point in the research and how it will be used in upcoming work in order to solve the overall problem. As of now, the cost function and method for true cost optimization is still being developed. However, we are capable of setting the number of radars to be optimized and maximizing areal coverage. As demonstrations, two examples will be presented: an X-band example, which maximizes coverage in the southern Plains using optimizable X-band radar systems and locked S-band radar systems, and a C-band example furnished in a similar fashion. The S-band radars are locked in the current WSR-88D locations, and the higher frequency radars are free to move about as needed for optimization.

a. *The Genetic Algorithm*

A genetic algorithm works via the theory of evolutionary principles. An initial population is entered into the algorithm (in this case, either 30 C-band or 125 X-band radar systems, in random locations), and a fitness value is evaluated based upon a cost function. The population is then modified slightly (mutated) and the fitness value is re-evaluated. If a predetermined goal is not met, the population is mutated again, and the process repeats. The results of each generation are stored and can be saved for future plotting and other output methods. In this case, we minimize a cost function which represents the inverse of areal coverage, and the algorithm is halted when the average fitness value changes by a set, relatively small number.

b. *Genetic Algorithm Implementation*

There are three main pieces to successfully running a genetic algorithm: a population must be designed and remain consistent in nature throughout the running of the algorithm (radar coverage shape and size), boundaries must be realistic and constant, and a cost function must be defined in order to have a basis for optimization. We will use natural boundaries which include the states of Kansas, Oklahoma, and Texas, and a cost function of:

$$C = \sigma_{total} - \Sigma\, \sigma_{inside}$$

where σ_{total} is the total number of possible covered locations and σ_{inside} represents a location which is actually covered by any radar. Due to the nature of this cost function, there must be a finite number of possible radar locations, which also translates to a finite number of locations which can be assessed for coverage. This both minimizes computational complexity as well as provides a multitude of avenues for future cost function expansion for other goals. An example using current WSR-88D radar sites and randomly placed C-band radar sites with coverage extending to a maximum scan elevation of 2 km is shown in Figure 1 (all height calculations use a 4/3 earth radius model). Each cross represents a possible radar location; blue crosses are not covered by any radar, while red crosses are covered by at least 1 radar. Each cross is assigned a value of 1, which changes to a 0 if it is covered. Using this method, the cost function, when minimized, results in a maximum number of covered locations.

4. PRELIMINARY RESULTS

For both examples, current S-band WSR-88D sites are fixed. Red circles represent coverage of the S-band radar systems out to a range in which the lowest elevation scan is below 2 km. Blue circles represent coverage of the higher frequency system. For the X-band example, CASA specifications for attenuation and power were assumed for coverage, while for the C-band example TDWR specifications were assumed.

a. *Initial X-Band Results*

An example X-band algorithm run is shown in Figure 2. The number of X-band radars must be set, and a value of 125 radars was used for this example. Generation 0 is the initialization, which was generated using a random placement of X-band radars. A total of 582 generations was needed in order to achieve the set goal, which was a minimal change in average fitness value (also referred to as optimization score). The score represents the number of possible radar sites which are NOT covered, meaning a lower score results in better total areal coverage. The score decreases with each generation until it reaches a minimum value.

b. *Initial C-Band Results*

A C-band algorithm run is shown in Figure 3. The number of C-band radars was 30 for this example. Again, generation 0 is a random initialization, and due to the higher coverage area per radar, only 234 generations were needed in order to reach an optimal state. A comparison between the number of chosen C-band radars versus the eventual optimization score and number of generations needed to reach the result is shown in Figure 4. Higher numbers of radars generally result in lower final scores (due to the larger area covered), but also require more generations to accomplish the goal due to higher computational complexity.

5. DISCUSSION

The examples provided show the ability for a genetic algorithm with a finite number of possible radar siting locations to determine optimal placement for maximum areal coverage. These are the initial steps in creating an algorithm which is capable of also minimizing cost. By incorporating multiple bands into a next-generation phased array radar network, such an algorithm can assist in designing a network which minimizes cost and complexity, maximizes coverage, and affords all the advantages of current proposals for single-band radar network replacements. The obvious current limitations involve the need to set the number of radars, as well as the lack of a 3-dimensional analysis tool. There are, however, potential uses for this result; networks which are adding radar systems with a set budget can use the algorithm in order to optimize placement for maximum coverage with a set number of radars. In addition, the siting locations can be changed in order to reflect realistic potential radar sites.

Upcoming work over the next year will focus on modifying the algorithm to maximize coverage while also minimizing cost. This is not a simple task, due chiefly to the increase in computational power needed. There are a number of methods which may be explored, ranging from simply including a different form of the cost function, to multiobjective optimization and the combination of multiple optimization techniques.

6. ACKNOWLEDGEMENTS

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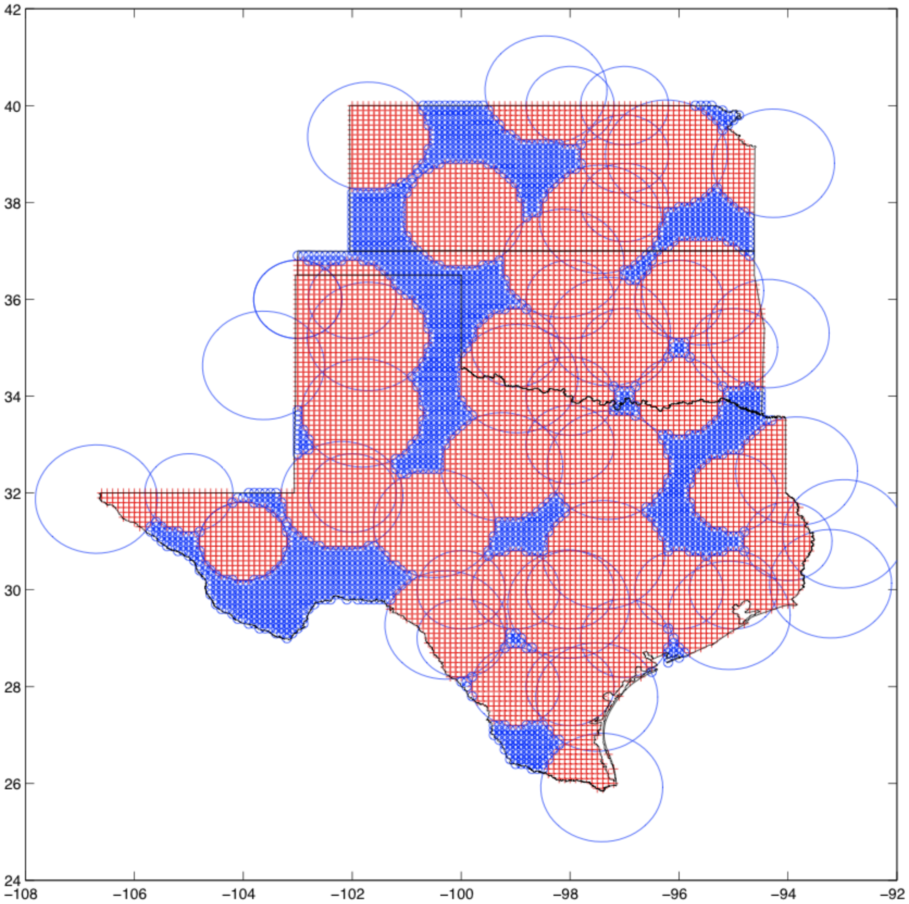

Figure 1: Illustration showing total possible radar sites (crosses), covered sites (red), and uncovered sites (blue). Circles represent radar coverage.

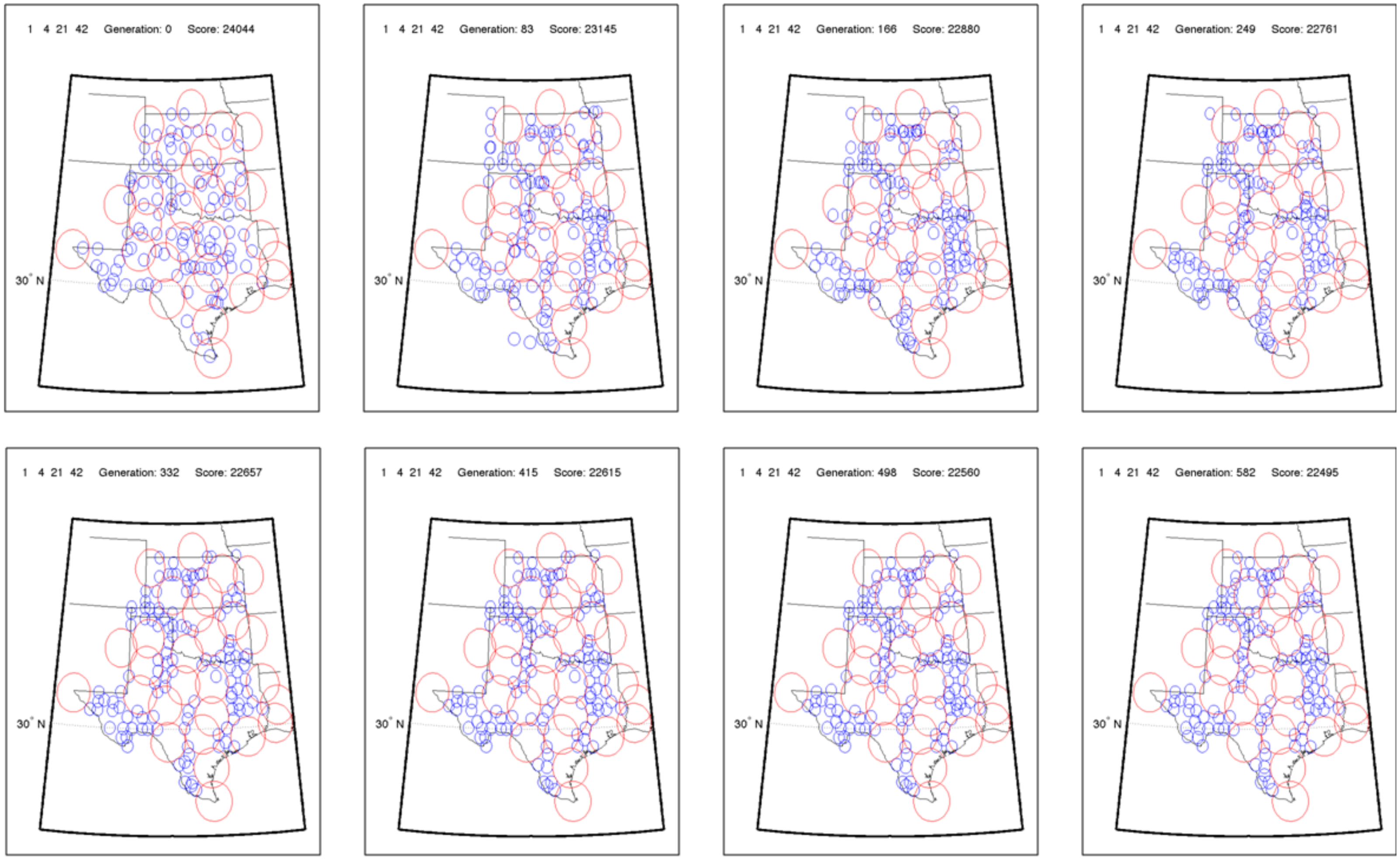

Figure 2: Sample set of 582 generations needed to optimize X-band radar placement (blue circles) amongst fixed current WSR-88D S-band radar sites (red circles).

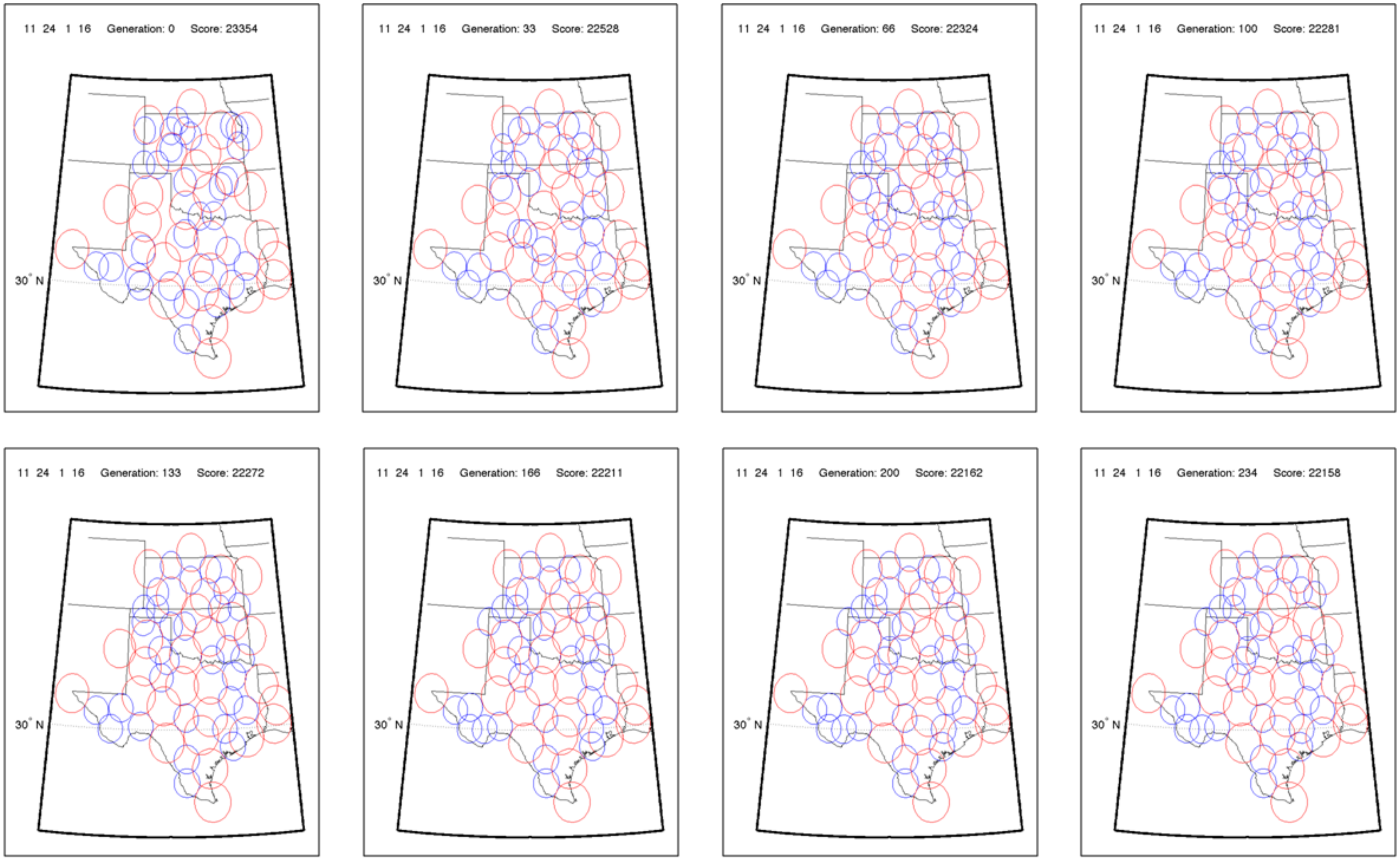

Figure 3: Sample set of 234 generations needed to optimize C-band radar placement (blue circles) amongst fixed current WSR-88D S-band radar sites (red circles).

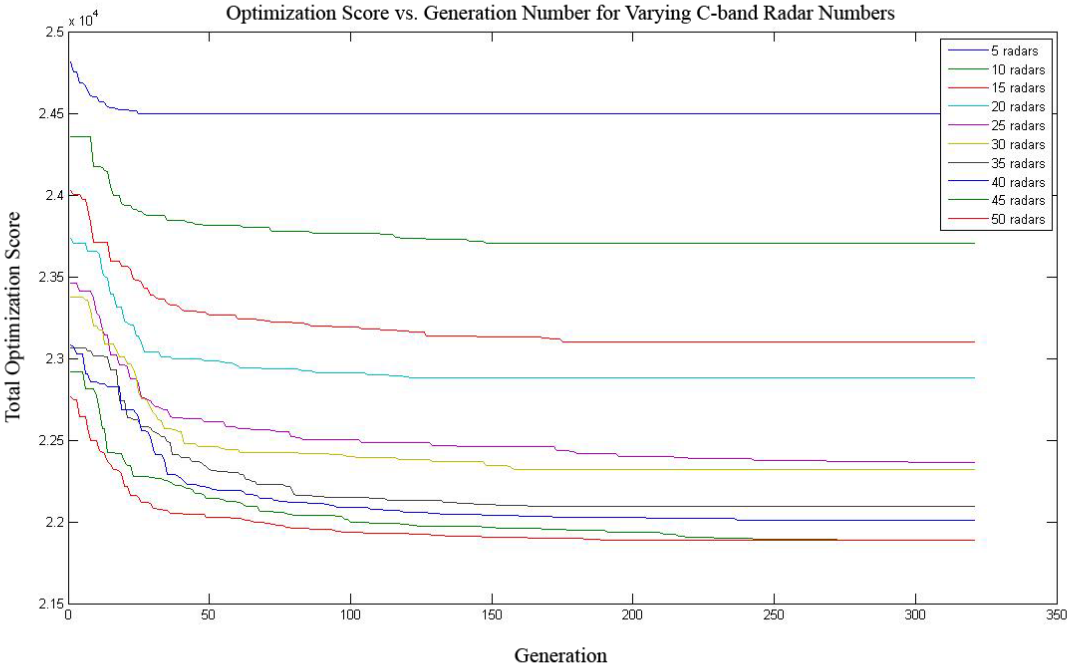

Figure 4: Comparison of optimization scores versus number of C-band radars. Current WSR-88D radar sites are fixed.