Optimal placement of weather radar network in complex terrain using swarm intelligence

Redouane Boudjemaa[1]

[1]*University MHamed Bougara of Boumerdes, 35000 Boumerdes, Algeria*
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Redouane Boudjemaa

Abstract.

This work proposes an accelerated particle swarm optimization (APSO) approach for the optimal placement problem of small low cost x-band mountain weather radars. Given a finite set of weather radars, a network is produced such that the geographical coverage area is maximised. By taking in consideration terrain blockage and low level radar beam elevation restrictions, the proposed method is capable of analysing multiple radar networks architectures in a restricted complex orography region and producing optimal result. The numerical results show a noticeable increase on the percentage of area covered. The proposed method can serve as an analysis tool for a decision support system to assist meteorologist in the selection of prime sites for the installation of weather radars.

1. Introduction

Weather Radar Networks (WRN) have been commonly used in both the prevision and research of weather systems.The Weather Surveillance Radar-1988 Doppler (WSR-88D) radar network of the USA has been efficiently used in the prediction, study and research of severe weather systems such as tornadoes. Another example of a collaborative radar network is the European Program on the Exchange of Weather Radar Information (OPERA) which is a joint project of 28 European countries within the framework of the Network of European Meteorological Services EUMETNET(Holleman and Delobbe (2007)). The network includes close to 160 operational radars with some 110 being Doppler radars. A difficult task in constructing these networks is determining adequate sitting sites of radars in order to meet certain conditions. As stated by Colle and Mass (1998), the benefits of such a WRN is the ability to study regional weather phenomena and most importantly over landscapes with complex orography such as mountainous regions (German and Joss). Minciardi et al. (2003) explains that contrary to a satellite observation of a weather system which only concentrate on the mass movement of cloud tops, the WRN can provide a more accurate measurement and real time data over a wide spread spatial region . This is due to the fact that the core of heavier precipitation lies at an altitude below one kilometre as pointed out by Wilson et al. (1980). The WRN provides also spatial distributed rainfall measurements, an important data for hydrology systems, in contrast to the rain gauges equipment which provides only a point measurement. Thus, not only WRN is utilised in weather prediction but also in the development of new hydrology models such as Cole and Moore (2009), Cole and Moore (2008), Victor et al. (2004) and Terblanche et al. (2001).

As indicated by Banta et al. (2013) radars are relatively large, high-powered systems, and their sitting site must allow a sufficient unobstructed scanning of the desired cloud features, since terrain interception effectively blocks the signal and limits the useful range. According to Committee to Assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain (2005), Site selection was based on providing maximum radar coverage in the priority areas required by the NWS, FAA, and DoD over highly populated regions while keeping installation and operational costs at a minimum.

The introduction of small and cheap X-BAND radars to the WRN would provide a regional coverage at a sub 1 km height levels essential for the provision of fast and very high resolution data. Such a reliable and accurate data would allow a real time update to weather forecast models resulting in the issue of important warnings of severe weather phenomenons (Heinselman et al. (2008)). Another essential factor in choosing such type of radars is their ease of installation and maintenance contrary to a C-BAND Doppler radar. Another important application of such an advanced and well covered network is the development of hydrological models, essential for water resources management, in the absence of sufficient installed rain gauges measurement tools.

Particle swarm optimization (Kennedy and Eberhart (1995)) is a population-based stochastic search algorithm which has become very popular for solving optimal placement problems in recent years. Pookpunt and Ongsakul (2013) utilised a Binary PSO algorithm in an optimal placement of wind turbines within a wind farm with an objective to extract the maximum turbine power output with minimum investment cost. Pradhan and Panda (2012) optimised sensor node locations in a wireless sensors network using a multiobjective PSO. By conducting a sensitivity analysis of different parameters they showed that the multiobjective particle swarm optimization algorithm is a better candidate for solving the multiobjective problem of deploying the sensors. (Kayal and Chanda (2013))

In this paper we present an algorithm based on accelerated particle swarm optimisation (APSO) to locate suitable sites for

 rboudjemaa@umbb.dz

the installation of WRs in a constrained geographical region. Given a number of available radars, the algorithm will place each and every one of them in a suitable geographical location maximising the total coverage area. Terrain blockage and radar beam elevation below a 1 km altitude are taken into account in the evaluation of a proposed radar placement site. This algorithm assumes that all possible sites have the same cost of installation and maintenance.

2. State of the Art

Limited literature exists in terms of optimisation methods applied to optimal placement of weather radars network. The approach that is often used in previous works is the selection of probable radar sitting sites based on a number of pre-set criterion. A systematic and objective approach in the placement of the Next Generation Weather Radar (NEXRAD)(WSR-88D) Doppler radars was investigated in the work carried out by Leone et al. (1989). A selection process with respect to various criterion such as:

- storms paths and other severe weather systems,
- landscape obstructions,
- locations of civilian and military airports,
- environmental impacts, and
- costs.

was used in the establishment of suitable sitting sites for the 136 radars.

An important breakthrough was achieved by Minciardi et al. (2003) by establishing for the first time a mathematical well defined optimisation problem. The total geographical region was divided to 285 subregions and four different covering layers were taken into account. Out of the 107 WRs, twenty were in the process of installation while the sitting sites of the remaining ones were evaluated through an optimisation of an adapted weighted set-covering problem. Again, in their work a limited number of potential sites were selected based on criterion such as:

- terrain blockage,
- geological stability (earthquake zones),
- electromagnetic pollution, and
- Communications to the site.

In the work undergone by Pedersen et al. (2010) in the design of small X-band weather radars network architecture, the following factors were taken into account in order of priority:

- Physical geographical features
- Power availability
- Distance requirements
- Existing radar and gauge installations
- Communication technology
- Bandwidth of communication channels
- Data formats.

The first four points all regard the location of the installation, while the latter three regard the communication.

A more recent and advanced work in determining the placement of WRs is investigated by Kurdzo and Palmer (2012). Through the utilisation of a genetic algorithm a maximisation of the coverage area within a set physical boundary condition is achieved. They provides three different optimisations problems to illustrate the flexibility and scope of their algorithm.

1. The first example takes as a placement criteria both severe weather climatology and population density data to optimize a small, dual-frequency network.
2. The second example takes into account a new X-band evaluated attenuation computed with respect to average convective rainfall as observed by the Oklahoma MESONET in the design of a dual-frequency network.
3. In their third example, they incorporate terrain blockage in combined mountainous/flat regions while optimizing a dual-frequency network.

3. Application of PSO to WRN optimisation

Particle swarm optimization (PSO) was developed by Kennedy and Eberhart (1995), based on swarm behaviour such as fish and bird schooling to a place with enough food or to seek safety. As described by Yang (2010), the movement of each swarming particle is determined by a combination of a stochastic element and a deterministic element. Each particle moves randomly while at the same time it is attracted toward a global leading particle (global best) $\mathbf{g}^*$ and a local leading particle (local best) $\mathbf{b_i^*}$. A particle i is defined by its position vector $\mathbf{x_i}$ and velocity vector $\mathbf{v_i}$. Its new positions is updated by:

$$\mathbf{x_i^{t+1}} = \mathbf{x_i}^{\mathbf{t}} + \mathbf{v_i^{t+1}} \tag{3.1}$$

where

$$\mathbf{v_i}^{\mathbf{t+1}} = \mathbf{v_i^t} + \alpha\epsilon_\mathbf{1} \odot [\mathbf{g}^* - \mathbf{x_i^t}] + \beta\epsilon_\mathbf{2} \odot [\mathbf{b_i^*} - \mathbf{x_i^t}] \tag{3.2}$$

is the new velocity vector obtained with respect to $\mathbf{g}^*$, $\mathbf{b_i^*}$, and two random vectors $\epsilon_\mathbf{1}$ and $\epsilon_\mathbf{2}$ taking values between 0 and 1. The product of two matrices $\mathbf{u} \odot \mathbf{v}$ is a Hadamard entry-wise product defined as $[\mathbf{u} \odot \mathbf{v}]_{ij} = u_{ij}v_{ij}$. The constants α and β represent the learning factors or acceleration constants. They represent the attraction that a particle has either toward its own success or toward the success of its neighbours.

In order to accelerate the convergence of the algorithm, the velocity vector is generated based on global best by a simpler formula

$$\mathbf{v_i}^{\mathbf{t+1}} = \mathbf{v_i^t} + \alpha(\epsilon - \frac{1}{2}) + \beta(\mathbf{g}^* - \mathbf{x_i^t}) \tag{3.3}$$

where ϵ is a random vector with values from 0 to 1. Based on this change, update of the location of a particle is calculated without the recourse to a velocity vector by

$$\mathbf{x_i}^{\mathbf{t+1}} = (1 - \beta)\mathbf{x_i^t} + \beta\mathbf{g}^* + \alpha(\epsilon - 0.5) \tag{3.4}$$

As explained in (Yang (2010)), this version will give the same order of convergence with typical values of $\alpha \approx 0.1 \sim 0.4$ and $\beta \approx 0.1 \sim 0.7$.

In applying APSO to the problem of optimal radar network, two important questions need to be addressed. The first question is how to deal with the vast space of solutions since in a finite geographical area we could end up with huge number of possible sites to choose from. The second question that need to be addressed is how to define an evaluation function which is easy and inexpressive to compute.

In our work, a modified explicit enumeration method is used similar to the one used by Kurdzo and Palmer (2012). The investigated geographical region is transformed into a gridded format with a resolution of approximatively 0.09° (1km) latitudinal and longitudinal spacing thus producing a matrix $\mathbf{A}_{M\times N}$. Each grid point is considered to be a either a potential sitting site or a point covered by the radar signal. When a possible site is selected (at a latitudinal and longitudinal position), a theoretical circle is drawn representing the range of the radar. Once this range is established, the algorithms determines the grid points included in this theoretical circle. Using a binary encoding, all grid points are set to zero initially. The selected site plus the points included in the theoretical circle are all set to one. Hence if $a_{i,j}$ is a grid point where i - j are latitude - longitude coordinates, then $a_{i,j} = 1$ if a point belongs to the circle and zero otherwise. The coverage area of all radars is then sum of all values of the grid points,

$$F = \sum_{i=1}^{M}\sum_{j=1}^{N} a_{i,j} \tag{3.5}$$

This fitness function would guarantee a mush more spread out radars due to the fact that a point in the grid is illuminated only once even when covered by two or more radars. The boundary conditions can be defined either by a lower and upper latitude and longitude or by a state/ country border.

The algorithm start by initialising randomly P particles each representing a different combinations of W radars placements. All P particles are evaluated using the fitness function (3.5) and the maximum P_{max} is selected. If there is an improve in the coverage area then the corresponding P_{max} particle is set as the global best and a new set of P particles are generated by (3.4). If the stopping condition is satisfied or the maximum number of iterations is reached then the algorithm is terminated.

4. Accounting for terrain blockage

When determining the theoretical coverage area of a any radar, the manufacturer assumes the absence of any physical obstacles that could reduce or obstruct the propagation of a radar signal. This is not always the case as for example, placing a radar close or on top of a mountain will severely alter the propagation of the radar beyond that point as illustrated in Figure 2.

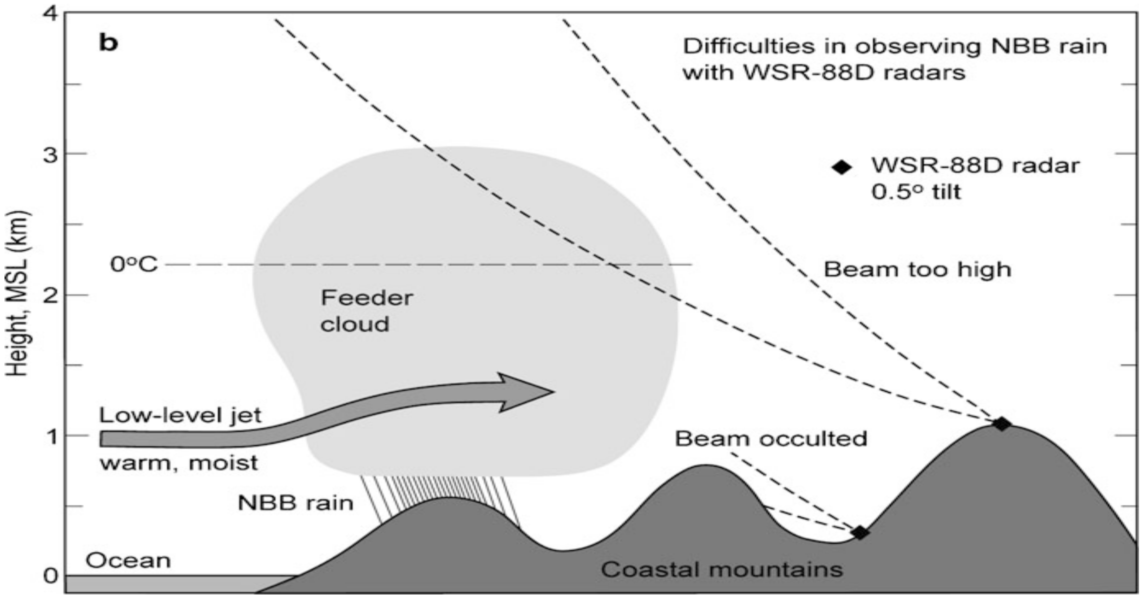


Figure 1: Conceptual diagram of shallow NBB rain in the Coastal Mountains of California, and problems encountered by operational WSR-88D radars in attempting to sample these clouds (White et al. (2003) ©American Meteorological Society)

The topography of the geographical region as shown as a grey surface in Figure **??** is an important factor in coverage alterations of X-BAND radars. Introducing this factor to the illumination process of grid points covered by a signal radar enhances further the realism of radar coverage area.

Hence, to incorporate this new factor to our model, a terrain data source must be selected. United States Geological Survey (GTOPO30) provides a global digital elevation data at a resolution of 30 arc seconds (≈ 1 kilometre) which is suitable for the utilised grid approach.

An assessment of signal propagation with respect to terrain blockage of each grid point representing a potential radar site or included inside the theoretical coverage area of a radar is performed using a 4/3 law (Doviak and Zrnic (1984)):

$$h = \sqrt{r^2 + a_e^2 + 2ra_e \sin\theta_e} - a_e \tag{4.1}$$

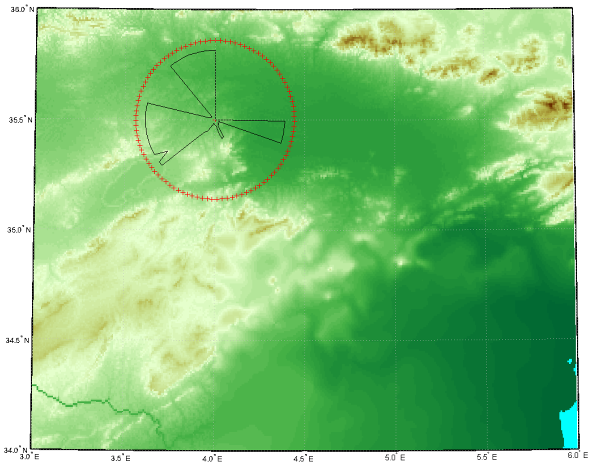
where h is height of beam in km, r is range of beam in km, θ_e is the elevation angle, and a_e is the effective earth's radius in km (4/3 the earth's radius).

Starting from the grid point representing a potential radar site and propagating the radar beam in 1 km range gates, the illumination process of grid points is terminated if one of these conditions is met:

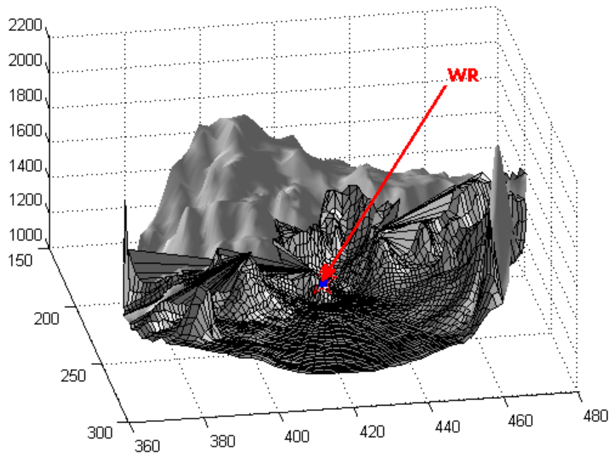
- the elevation at the actual grid point is greater than the height of the beam $h <$ elevation (i_{xy}),
- the height of the beam exceeds a pre-set upper limit $h >$ Upper limit,
- the distance from the potential radar site is greater than the theoretical range limits set by the antenna manufacturer $r >$ theoretical range.

The first condition implies that the radar beam has encountered an obstacle and can not propagate further beyond that point. The second condition allows the user to impose a limit on the height of the radar beam. This mean that if a user is interested only on weather system at altitude lower than 1 km, the upper limit is in this case set to 1 km. The last condition ensures that no grid point are illuminated beyond the theoretical range of the radar.

A significant change of the radar coverage area is observed when applying the three above conditions which are visible in Figure 2. The circle represents the theoretical range of the radar sitting at the centre of the circle while the contour line inside represents a near realistic state of the range when submitted to terrain blockage. This reduction in range is clearly observable in Figure 2a. The smooth grey surface represents the circular area that is theoretically covered by the radar, while the black dashed surface represents the realistic coverage of the radar. From this figure, we can see clearly that the difference between the theoretical coverage area and the realistic area is nearly 50%. This difference would range from 100% by placing a radar on position at an elevation higher than the pre-set maximum altitude to a 0% by installing the radar in perfectly flat region. By accounting for terrain blockage in the proposed algorithm, a more accurate representation of radar coverage is obtained which in return leads to a more optimal placement of radars.



(a) severe restrictions of a radar signal



(b) 3D view of a difference between a theoretical range (in grey) and a realistic range (dark mesh)

Figure 2: Examples of weather radar signal submitted to terrain blockage and radar beam elevation

5. Numerical results

The analysis were conducted with a 1.1° radar beam elevation angle and a tower height of 15 m. A 1 km altitude upper limit to the radar beam is utilised while the theoretical range of the X-BAND radar is set to 45 km.

The results displayed in Figure 3 were obtained using a swarm with 5 , 10 and 15 particles to an optimal placement problem of 5 radars. The geographical area selected for the first result was the central coastal region of Algeria between longitude:3°E and 5°E and latitude: 36°N and 37°N which is part of the Atlas Tellien mountains. Two stopping criterion were imposed on the APSO algorithm, the first being pre-set maximum number of iterations while the second is a user selected value (0...1) representing the desired percentage of area covered by the weather radar network.

Figure 3a shows the changes in the percentage of the area covered with respect to the number of iterations. Starting from an initial radars area coverage of less than 60% after only 100 iterations the algorithms increases the total area of radars coverage to an average of 80% for all three cases. At the end of 500 iterations, a coverage zone of nearly 85% was obtained with 15 particles. The computational time of the obtained 500 iteration was bellow an hour for 5 particles and over an hour and a half with 15 particles. Figure 3b shows a three dimensional placement of the global best solution detected by the APSO algorithm after 500 iteration. The yellow polygon positioned above the surface represents the realistic coverage area of each radar.

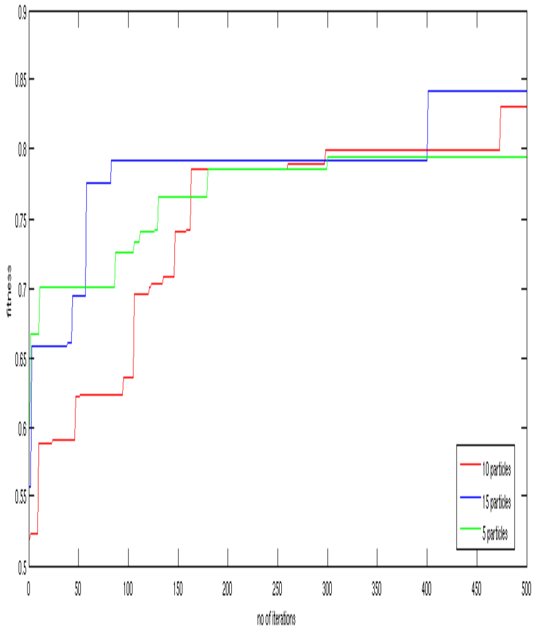
For the second case, the selected area was the Ahaggar mountains in the centre of the Algerian desert between longitude:3°E and 9°E and latitude: 22°N and 27°N. Again, two stopping criterion were imposed on the APSO algorithm, a pre-set maximum number of iterations and a user selected value (0...1) representing the desired percentage of area covered by the network. The results displayed in Figure 4 were obtained using a swarm with 5 , 10 and 15 particles to an optimal placement problem of 15 radars.

Figure 4a displays the changes in the percentage of the area covered with respect to the number of iterations. Starting from an initial radars area coverage of near 22%, the algorithm has reached at the end of 500 iterations a coverage of nearly 27% with 5 particles and about 28.5% for both 10 and 15 particles. The computational time of the obtained 500 iteration was about 24 hours with 15 particles.

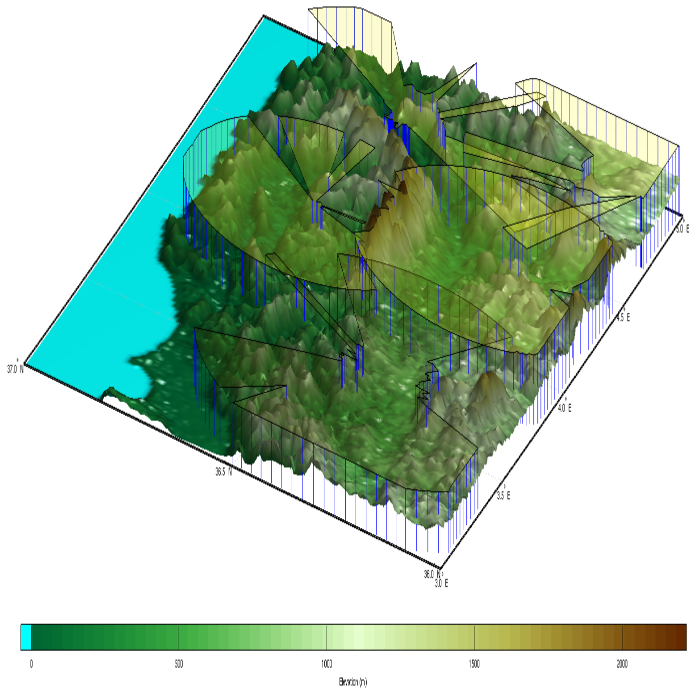
As before, Figure 4b illustrates both the positioning and the coverage delimitation of the global best solution detected by the APSO algorithm after 500 iteration.

As expected, the optimum placement of the radars in both cases are mostly located in shallow part of the mountains rather than the peak. This confirms the description of the ideal radar site indicated by Banta et al. (2013) which from physical considerations would be at the centre of a shallow doughnut of slightly higher ground. This is due to the fact that if you place a radar at high level then the radar beam will most likely exceeds the desired 1 km altitude. Placing a radar in a site closer to a mount would restrict the propagation of its beam and thus limiting its coverage area.

Another important result is the reduction of the areas of intersection between different radars. Figure 4b confirms a well spread out network of radars where intersection points are adequately minimal.

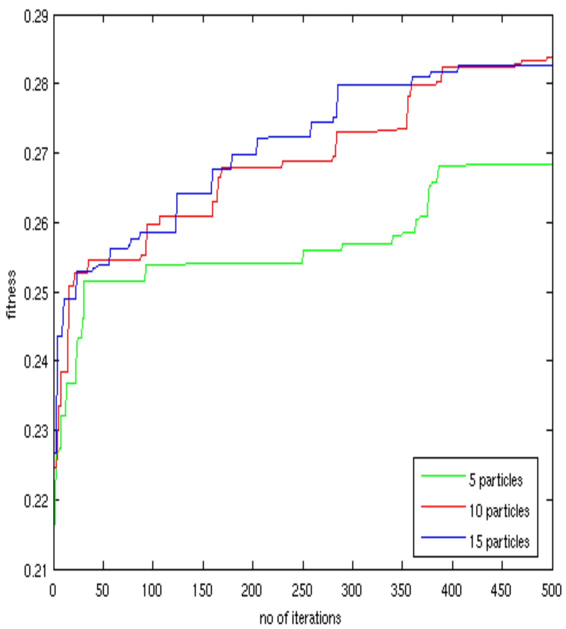


(a) Fitness of 5 WRs with 5,10 and 15 particles

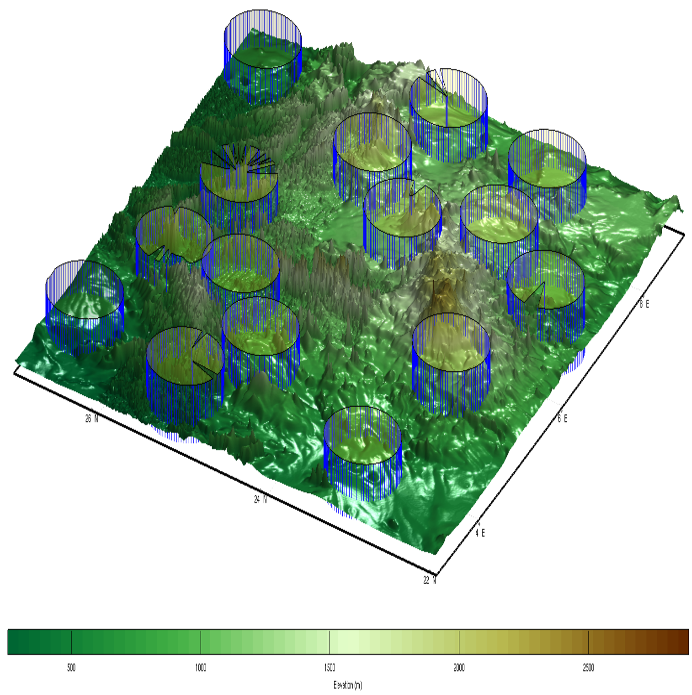


(b) Placement of the 5 WRs after 500 iterations

Figure 3: Results obtained using the APSO approach for 5 WRs and a swarm of 5, 10, and 15 particles after 500 iterations



(a) Fitness of 15 WRs with 10 and particles



(b) Placement of the 15 WRs after 500 iterations

Figure 4: Optimal placement of 15 WRs with a swarm of 5,10, and 15 particles after 500 iterations LAT:[22-27] LON:[3 9]

6. Conclusion

An APSO based algorithm for determining optimal placement of radars would constitute a perfect start for meteorologists to design a weather radar network. Given enough radar technical information and terrain data, the algorithm is capable of pinpointing suitable radar sitting sites at a relatively short time and sufficient accuracy. This tool should reduce cost through the reduction of suitable sites that are evaluated on field by experts.

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