# Polar Lights Optimizer: Algorithm and Applications in Image Segmentation and Feature Selection

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# Abstract

This study introduces Polar Lights Optimization (PLO), a metaheuristic algorithm inspired by the aurora phenomenon or polar lights. The aurora is a unique natural spectacle that occurs when energetic particles from the solar wind converge at the Earth's poles, influenced by the geomagnetic field and the Earth's atmosphere. By analyzing the motion of high-energy particles and delving into the underlying principles of physics, we propose a unique model for mimicking particle motion. This model integrates both gyration motion and aurora oval walk, with the former facilitating local exploitation while the latter enabling global exploration. By synergistically combining these two strategies, PLO achieves a better balance between local exploitation and global exploration. Additionally, a particle collision strategy is introduced to enhance the efficiency of escaping local optima. To evaluate the performance of PLO, a qualitative analysis experiment is designed to assess its ability to explore the problem space and search for solutions. PLO is compared with nine classic algorithms and eight high-performance algorithms using 30 benchmark functions from IEEE CEC2014. Furthermore, we compare and analyze PLO with the current state-of-the-art methods in the field, utilizing 12 benchmark functions from IEEE CEC2022. Subsequently, PLO is successfully applied to multi-threshold image segmentation and feature selection. Specifically, a PLO-based multi-threshold segmentation model and a binary PLO-based feature selection method are developed. The performance of PLO is also evaluated using 10 images from the Invasive Ductal Carcinoma (IDC) medical dataset, while the overall adaptability and accuracy of the feature selection model are tested using 8 medical datasets. These results affirm the emergence of PLO as an effective optimization tool ready for solving real-world problems, including those in the medical field. The source codes of PLO are available in <https://aliasgharheidari.com/PLO.html> and other websites.

Keywords: Metaheuristic algorithms; Polar Lights Optimization; Medical applications; Multi-threshold image segmentation; Feature selection

|  |  |  |  |
| --- | --- | --- | --- |
| **Nomenclature** | | | |
| PLO | Polar Lights Optimization |  | A random number with values between . |
| MAs | Metaheuristic algorithms |  | The collision probability |
|  | The population size |  | Mass of the particle |
|  | The problem's dimension |  | Velocity vector of the particle |
|  | The PLO population |  | Charge of the particle |
|  | The energetic particles |  | Geomagnetic field intensity |
|  | Upper and lower bounds of the solution space |  | The center-of-mass position of the energetic particle population |
|  | The current optimal solution computed by the algorithm |  | The weights of the gyration strategy and the auroral ellipse strategy |
|  | Variation of the auroral oval walk |  | Current and maximum number of iterations |
|  | Damping factor |  | The optimal solution searched by the meta-heuristic algorithm |

# Inspiration from the polar lights, or aurora borealis

The aurora is a beautiful natural phenomenon of electrical impulses occurring at altitudes between 80 and 500 kilometers above the horizon. The Earth's magnetic field forms a strong magnetic shield from the South Pole to the North Pole, manifesting itself in a pattern of curved magnetic lines of force. As a result, energetic particles are funneled toward the poles in a spiral motion, colliding with the many molecules of atmospheric gas over the poles. These collisions produce luminescence, as shown in Figure 1. Auroras form as a result of the interaction between solar activity, the Earth's magnetic field, and the atmosphere[56].

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Figure 1. An aurora borealis light curtain high in the sky[[1]](#footnote-1)

Initially, the main driving force behind the formation of auroras is solar activity. On the surface of the Sun, there exists a high-temperature plasma containing charged particles commonly referred to as the solar wind. The charged particles and their complex and variable motion processes are the focus. These particles carry enormous amounts of energy from the Sun into the vastness of cosmic space. In addition, the Earth possesses a powerful magnetic field that arises from the rotation of its core and the motion of its outer core. This magnetic shield wraps around the Earth, forming a protective layer known as the magnetosphere. When charged particles from the solar wind enter the Earth's magnetosphere, they interact with the magnetic field. Changes in the trajectory of charged particles are due to the Earth's magnetic field. Specifically, it will encounter the Lorentz force and be deflected in a specific direction, thus entering an orbit consisting of the geomagnetic field. As shown in Figure 2, this orbit will guide the charged particle close to the Earth's polar regions, the North and South Poles. At this stage, the charged particles have two velocity components: parallel to the magnetic field and perpendicular to it. As a result, they are in gyratory motion while traveling along the magnetic field lines. This marks the beginning of the first major phase, in which the trajectories of the energetic particles undergo their first change. During this phase, the charged particles will gradually encounter the atmosphere over the polar regions and collide with gas molecules in the atmosphere. Then, the energy initially possessed by the charged particles will gradually be transferred to the air molecules, causing them to ionize and subsequently glow. Due to the loss of energy, the trajectory radius of the charged particles will be significantly affected and reduced, which again leads to a change in their trajectory.

Figure 2. Solar wind energetic particles enter the earth's magnetic field lines.

As a result of the energy transfer due to the collision, the gas molecule is excited, and the electrons in the ground state jump from one energy level to another and then back to the ground state. During the energy level jump, the gas molecule releases energy and produces photons. These photons are the visible light that makes up the aurora borealis. Different gas molecules have different energy level structures and emission spectra. For example, oxygen molecules emit green and red light, and nitrogen molecules emit violet and blue light. As the collision continue, the energy contained in the energetic particles is gradually lost, leading to the transition to a significant phase. These particles encounter considerable obstacles in directly bombarding polar ice and the ground due to atmospheric obstructions. Instead, they pause briefly in the atmosphere and gather to form a luminous ring, as shown in Figure 3. This glowing ring band is usually oval around the polar axis, hence the name "auroral oval". Charged particles that are in an auroral oval undergo further collisions with gas molecules. More specifically, the energy of electrons drops relatively quickly and is absorbed by the atmosphere, while the energy of protons drops more slowly. After protons collide with gas molecules, some of them will be absorbed by the atmosphere, while the other part will deviate from the ring band region in the atmosphere and bounce along a different path. The periods of magnetic quiescence and magnetic perturbation in the Earth's magnetic field affect the auroral oval, causing irregular changes that manifest as irregular expansion and contraction. Thus, in the second major phase, the trajectory of the particle undergoes a third change. After three trajectory changes, the journey of the particles towards the Earth will end.

Figure 3. Aurora oval in the Earth's Arctic

In summary, the formation of auroras is determined by the interaction between charged particles in the solar wind and the Earth's magnetic field. This interaction causes the charged particles to enter the Earth's atmosphere and contact with gas molecules, thereby exciting them and releasing energy in the form of photons, ultimately forming visible bands of colored light. In this study, we designed a new model to simulate this complex process. The model includes an in-depth study of the principles of aurora formation, precise tracking of the particle trajectories, division of the entire process into two distinct phases, and three changes to the trajectory. Based on this elaborate model, three strategies are proposed to lead to Polar Lights Optimization (PLO).

# 3. Methodology

This section gives the inspiration for PLO, i.e., an optimization strategy based on the motion process of energetic charged particles guided by a magnetic field. The mathematical model is expounded upon, enabling comprehension of PLO's structure through the presentation of pseudo-code, a flowchart, and the computation of the algorithm's time complexity.

## 3.1 Mathematical model of the PLO

Inspired by the phenomenon of aurora borealis, a stream of charged particles (solar wind) moves in the air near the north and south poles of the Earth under the influence of the magnetic field environment and displays a variety of shapes and brilliant colors in the night sky. Auroras are produced under the atmosphere, magnetic field, and high-energy charged particles. The behavior of auroras is attributed to various dynamic processes of interaction between charged particle streams and magnetic fields [57]. In this study, the gyration motion is proposed through the motion process of energetic charged particles spiraling forward around magnetic lines of inductance; then, the aurora oval walk is proposed by synthesizing the energies, velocities, and trajectories of charged particles, as well as the compositions and conditions in the atmosphere, where auroras present an elliptical luminous ring belt in the sky. Finally, the particle collision strategy is proposed through the phenomenon of energetic charged particles colliding with one another continuously on their flights.

### 3.1.1 Initialization phase

In PLO, the iterative process will start with an initial population that is generated based on pseudo-random numbers. As described in Eq. (1), the entire population is represented in the form of a matrix with rows and columns in size, where denotes the size of the candidate solutions contained in the population and denotes the scalable dimension of the solution space.

|  |  |
| --- | --- |
|  | (1) |

where and denote the boundaries of the solution space, and denotes a random number sequence that takes values in . In PLO, the travel of a swarm of energetic charged particles flying towards the Earth around the magnetic susceptor towards the polar center is simulated with a search agent in the solution space.

### 3.1.2 Gyration motion

This section will delineate the method for searching for optimal solutions in PLO, namely the gyration motion, inspired by the extensive journeys of high-energy particles toward the Earth. Roughly 150 million kilometers from Earth, the Sun continuously emits electrons and protons towards our planet, which is entirely enveloped by its magnetic field, extending outward from the Earth by approximately 50,000 to 65,000 kilometers [58]. As these particles approach Earth, they encounter resistance from the Earth's magnetic field and radiate in various directions under its influence. During this process, charged particles approaching Earth interact with its magnetic field, experiencing rotational motion along magnetic field lines, a phenomenon describable by the Lorentz force. Mathematically, assuming a charge and velocity for the charged particle within Earth's magnetic field ), the Lorentz force can be expressed as Eq. (2):

|  |  |
| --- | --- |
|  | (2) |

The causes a centripetal force to be exerted on a charged particle, resulting in its gyratory motion along the magnetic lines of force in a magnetic field. Also, the equation of a charged particle can be described by the Lorentz force and Newton's second law:

|  |  |
| --- | --- |
|  | (3) |

where is the mass of a charged particle. This equation describes the variation of the velocity of the charged particle with time so that its trajectory in the magnetic field can be determined. By joining the above two equations (Eq. (2) and Eq. (3)), a first-order ordinary differential equation can be obtained, as shown in Eq. (4):

|  |  |
| --- | --- |
|  | (4) |

This differential equation describes the change in velocity of the charged particle over time. Solving this differential equation yields the law governing the variation of the particle's velocity with time, providing insight into its motion within the Earth's magnetic field, as depicted below.

Rearrange the two sides and integrate them simultaneously, with the interval of integration from the initial velocity to and the time from 0 to :

|  |  |
| --- | --- |
|  | (5) |
|  | (6) |
|  | (7) |
|  | (8) |
|  | (9) |

In an ideal scenario, the aforementioned equation adequately describes the motion of charged particles within Earth's magnetic field, as illustrated in Figure 4. However, these high-energy particles encounter resistance from air molecules in the atmosphere, resulting in the non-smooth circling motion. This non-smooth circling motion is due to the damping effect of the atmosphere. As charged particles enter the atmosphere, collisions with atmospheric molecules diminish their kinetic energy, causing the radius of their circular motion to decrease.

Figure 4. Charged particles gyrate around the magnetic line.

After accounting for the damping effect of the atmosphere on charged particles, we can incorporate this damping phenomenon into the equation governing the variation of the particle's velocity with time. In this equation, we introduce a damping factor , representing the rate of decay of the particle's velocity. Thus, the equation (Eq. (4)) describing the variation of the charged particle's velocity with time can be modified accordingly, as in Eq. (10).

|  |  |
| --- | --- |
|  | (10) |

The modification results in a nonhomogeneous first-order linear differential equation, Eq. (10). By employing the method of constant variation, assuming a solution , where and are undetermined coefficients. Substituting this into the equation, we obtain:

|  |  |
| --- | --- |
|  | (11) |

Solving yields , so the final solution to the equation Eq. (12) is:

|  |  |
| --- | --- |
|  | (12) |

where is the constant of integration, in this equation the charge carried by the charged particle, the mass and the strength of the earth's magnetic field do not change. For simplicity, in this strategy, , , and take the value of 1, and is 100. The damping factor is a random value taking the value of , and the fitness evaluate process of the algorithm is utilized within the strategy to simulate the time () course of Eq. (12).

In this section, the gyration motion within PLO introduces an equation describing the variation of charged particle velocity over time. This equation combines the Lorentz force law and Newton's second law. Moreover, considering the damping effect exerted by the atmosphere on the charged particles, a damping factor is introduced into the equation, enhancing its precision.

When charged particles undergo gyration motion, they exhibit the following characteristics:

(1) Prior to coming into contact with magnetic field lines, charged particles follow their initial trajectory. Only when they enter the influence range of the Earth's magnetic field do they gradually alter their path, spiraling around the magnetic field lines.

(2) During the gyration motion, particles experience damping effects generated by the atmosphere, causing a reduction in their energy and consequent decrease in velocity.

(3) The damping effects of the atmosphere become increasingly pronounced as the particles travel further.

(4) Despite the occurrence of damping effects, the ultimate destination of particle flight remains unchanged (the Earth's poles).

This strategy enhances the algorithm's capability for local exploitation, enabling it to finely exploit local regions and explore optimal solutions within those regions.

### 3.1.3 Aurora oval walk

This section describes the auroral oval walk in PLO, a method that helps to search the solution space efficiently. The idea of this strategy originated from the extensive study of auroras by astronomical observers. They concluded that auroras tend to form along an elliptical band called an auroral oval. The size of the auroral oval depends on the north-south component of the interplanetary magnetic field, and its boundaries vary with geomagnetic activity. The Earth's complex atmosphere further contributes to the movement of various energetic particles in this phenomenon.

The intricate fluctuation of the auroral oval walk will significantly impact the global search. It is the unpredictable chaos that fulfills the need of the PLO for a fast global search of the solution space. It is worth noting that Levy Flight (LF) is often used in MAs to enhance global exploration because it is essentially a random non-Gaussian Walk. Its step values are dispersed based on the Levy stable distribution. The LF can be expressed in Eq. (13) as follows:

|  |  |
| --- | --- |
|  | (13) |

where denotes an important LF index of adjustment stability and is the step size.

In the auroral oval walk, the energetic particles simulated with LF are affected by geomagnetic activity as well as the atmosphere and exhibit contraction of the auroral oval boundary in the polar direction and expansion in the equatorial direction. The specific change process is shown in Eq. (14):

|  |  |
| --- | --- |
|  | (14) |
|  | (15) |

where is the center-of-mass position of the energetic particle population, calculated by Eq. (15). is the current position of the energetic particles, while represents the tendency of the particles to move. is a complex variation of the auroral oval simulated by the dispersed distribution of the LFs, which drive energetic particles between the poles and the equator. The motion of each particle is briefly simulated as shown in Figure 5.

Figure 5. The aurora oval walk

This strategy enhances PLO's global exploration capabilities, allowing it to quickly navigate the entire solution space and search for valuable regions.

In the PLO, the search process follows a unique pattern. It comprises two main motion patterns: gyration motion and aurora oval walk, each representing distinct search strategies and behavioral characteristics. Together, they constitute the trajectory of particles flying from the start (the Sun) to the end (the Earth's poles).

Firstly, the gyration motion manifests as particles spiraling along the Earth's magnetic field lines, exhibiting slow movement along fixed trajectories. This motion pattern emphasizes local exploitation and fine adjustments, aiming to explore local solution spaces more deeply to find local optima or optimize the local structure of the current solution. This aligns with the local search phase in MA, where subtle adjustments and small steps are taken to enhance the quality of solutions, bringing them closer to the optimal solution.

Secondly, the aurora oval walk involves rapid motion around candidate points for the best solution or local optima. This pattern emphasizes global exploration characteristics, with particles exploring the solution space with larger steps to discover more valuable regions. This corresponds to the global exploration phase in MA, where the solution space is searched with larger step lengths to find global optima or better solutions.

Therefore, this paper combines these two strategies in PLO, and the proposed new computational model is represented by Equation (16).

|  |  |
| --- | --- |
|  | (16) |

where is the position of the energetic particle after completing the update, and represents the interference brought by factors such as the uncontrollable environment for the particle and is a value taking the value of . To maximize the efficiency of local exploitation and global exploitation during the process, two adaptive weights and are introduced that change with each iteration of the algorithm. as calculated in Eq. (17) and Eq. (18) are obtained:

|  |  |
| --- | --- |
|  | (17) |
|  | (18) |

where and control the weights of the gyration motion and the auroral oval walk in Eq. (16), as shown in (a) in Figure 6, the weight of will increase with ; as shown in (b) in Figure 6, the weight of , , gradually decreases. As the algorithm iterates, global search and local exploitation rely on the changing weights to achieve a balance and explore the optimal solution.

Figure 6. Trajectories of change in and

In summary, the particle motion in the PLO encompasses both global exploration and local exploitation. Comprehensive optimization of the solution space is achieved by combining the gyration motion and aurora oval walk motion patterns. This design aims to strike a balance between global search and local optimization, intending to effectively find the optimal solution or solutions close to optimality within the solution space.

### 3.1.4 Particle collision

Robust global and strong local strategies are not the sole pivotal constituents of a refined algorithm. Additionally, a more potent capability to evade convergence into local optima or break free from them is imperative. Consequently, this section introduces a particle collision strategy to boost the capacity to jump out of a stuck situation.

In the solar wind, charged particles such as electrons and protons travel from the sun to the earth at high speeds and collide with each other as they hit the atmosphere. When they enter the Earth's magnetic field and are guided by magnetic lines of force, they move along the lines near the Earth's polar regions. During this process, energetic particles that have changed speed and direction collide violently with each other. These collisions can lead to the transfer of energy and the conversion of energy forms, further enhancing the process of aurora formation. Collusions can lead to changes in the speed and direction of the particles and scatter them in different areas. In addition, they can stimulate the excitation and ionization of more particles, thus enhancing the brightness and complexity of the aurora [59]. Thus, particle collisions play a crucial role in the formation of auroras.

Inspired by this, a particle collision strategy is proposed. The chaotic collision between particles allows PLO to leave the local optimal. In this strategy, if we focus on the current moving particle, it may chaotically collide with any particle in the particle swarm to create a new position along the way, as shown in Figure 7. If a particle is the focus of attention, it may randomly drift out of the established flight trajectory and collide with any of its surrounding particles. When the particle it is about to collide with is used as a reference, the collision may occur at any angle, just like the uncertain outcome of a novice billiards game. Also, minor collisions can occur when energetic particles fly from the solar to the earth. However, as these particles enter the atmosphere and converge within the auroral oval, collisions occur more frequently, resulting in the ever-changing shape of the aurora. The mathematical model is shown in Eq. (19):

|  |  |
| --- | --- |
|  | (19) |
|  | (20) |

where represents any particle in the particle cluster. Collisions between particles become more frequent as the algorithm proceeds and are therefore controlled by the collision probability , calculated by Eq. (20). and are random values, taking values in .

Figure 7. Chaotic collisions between particles.

## 3.2 The proposed PLO

In essence, this paper draws inspiration from the aurora, a captivating physical phenomenon, and melds it with the principles of physics to devise PLO. Search agents are likened to high-energy particles emanating from solar radiation towards the Earth, all subject to the influences of magnetic fields and atmospheric conditions as they journey towards the Earth's poles. Nevertheless, owing to various uncontrollable factors, the trajectory of each particle remains unpredictable, yet converging toward the vicinity of the polar regions constitutes the ultimate destination of their journey.

In PLO, initially charged, the geomagnetic force influences particles and moves them towards the poles, continuously colliding with gas molecules in the atmosphere and gradually impeding their gyration motion. Subsequently, these particles gather near the upper atmosphere of the poles, forming an elliptical-shaped region known as the auroral oval. Due to the irregular deformation of the auroral oval, this elliptical ring-shaped region becomes unstable, contracting towards the poles during magnetic quiescence periods and expanding towards the equator during disturbance periods.

Inspired by these phenomena, we based our proposal on the Lorentz force theorem and Newton's second law to propose a modified modeling equation for the variation of charged particle velocity over time, incorporating a damping factor. Furthermore, we propose an auroral oval walk strategy based on the auroral oval phenomenon. Then, by combining the gyration motion and aurora oval walk motion patterns, we construct comprehensive optimization progress to assist PLO in global exploration and local exploitation. Finally, we introduced the particle collision strategy to facilitate interactions among particles, enabling the PLO to effectively escape from local optima states.

As shown in Algorithm 1, the PLO’s pseudo-code can better help to understand the process. In Figure 8, flowcharts will clearly show the structure.

|  |
| --- |
| **Algorithm 1** PLO’s pseudo-code |
| Parameters initializing: ,,  Initialize high-energy particle cluster .  Calculate the fitness value .  Sort according to .  Update the current optimal solution .  **While**  Calculate the velocity for each particle, according to Eq. (12).  Calculate aurora oval walk for each particle, according to Eq. (14).  Calculate weights and according to Eq. (17) and Eq. (18).  **For** each energetic particle **do**  Updating particles using Eq. (16).  **If** and  Particle collision strategy: update particle using Eq. (19).  **End If**  Calculate the fitness .  .  **End For**  **If**  Iterating over using the greedy selection mechanism.  **End If**  Sort according to .  Update the optimal solution.    **End While**  **Return the** . |

Figure 8. The flowchart of PLO

1. Pictures obtained from <https://pixabay.com/> as copy right free images   
   (a) https://pixabay.com/photos/aurora-borealis-lake-snow-aurora-5599375/   
   (b) https://pixabay.com/photos/aurora-polar-lights-northern-lights-1190254/ [↑](#footnote-ref-1)