Journal of Atmospheric and Solar-Terrestrial Physics 133 (2015) 178–184

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Improvement of automatic scaling of vertical incidence ionograms by simulated annealing

Chunhua Jiang*, Guobin Yang, Ting Lan, Peng Zhu, Huan Song, Chen Zhou, Xiao Cui, Zhengyu Zhao, Yuannong Zhang

Ionosphere Laboratory, School of Electronic Information, Wuhan University, 430079, Wuhan, Hubei, China

A R T I C L E I N F O

Article history:
Received 25 May 2015
Received in revised form
13 August 2015
Accepted 4 September 2015
Available online 7 September 2015

Keywords:
Ionogram
Automatic scaling
Simulated annealing
Ionosphere

A B S T R A C T

The ionogram autoscaling technique is very important for facilitating the statistical investigation of the ionosphere. Jiang et al. (2013) proposed an autoscaling technique for extracting ionospheric characteristics from vertical incidence ionograms. However, extensive efforts are invested in continuously improving the performance of that. The simulated annealing (SA) is used to improve the autoscaling technique in this paper. To be capable of automatic scaling of ionograms recorded at different locations, the SA is applied instead of Empirical Orthogonal Functions (EOFs) to search the best-fit parameters in the autoscaling technique. In order to validate the improvement of this autoscaling technique, ionograms recorded at Wuhan (30.5°N, 114.3°E), Puer (22.7°N, 101.05°E) and Leshan (29.6°N, 103.75°E) are investigated by comparing the autoscaled results with the values scaled by an operator. Results show that the presented work is efficient for scaling of ionograms recorded at different geographic positions. Moreover, the additional procedure can improve the accuracy of the autoscaling technique compared to results presented by Jiang et al. (2013).

1. Introduction

Ionosonde is a direct and effective means of investigating the ionosphere for the ground-based observations, and it has a long standing history. To study the ionosphere, the time delay of radio signals propagated in the ionosphere and the corresponding working frequency are recorded simultaneously by the ionosonde. Then, times delays replaced with virtual heights are plotted against working frequencies. The corresponding image is referred to as an ionogram. Ionospheric characteristics can be extracted from ionograms. At an early stage, manual scaling of ionograms is used to obtain characteristics of the ionosphere from ionograms. With the development of ionosondes and the generation of a large quantity of ionograms, the manual scaling method cannot meet the practical application for investigating the ionosphere. Thus, ionogram autoscaling techniques have been proposed and developed with the development of computing technologies.

In the past few decades, much work (Galkin, 1962; Reinisch and Huang, 1983; Fox and Blundell, 1989; Igi et al., 1993; Tsai and Berkey, 2000; Scotto and Pezzopane, 2002; Zabotin et al., 2006; Ding et al., 2007; Rice et al., 2009; Liu et al., 2009; Stankov et al., 2012; Chen et al., 2013) has been devoted to ionogram autoscaling techniques. However, achieving a good quality of results is always a challenging task using autoscaling techniques. Recently, the Automatic Real-Time Ionogram Scaling with True-height (ARTIST) developed by University of Lowell (Reinisch and Huang, 1983) has been gradually improved and evaluated by many studies (Galkin et al., 1996; Reinisch et al., 2005; Galkin and Reinisch 2008; Bamford et al., 2008; Stankov et al., 2012). An alternative procedure for automatic scaling of ionograms, Autoscala, was designed by Scotto and Pezzopane (2002). Procedures of scaling of Es (Scotto and Pezzopane, 2007) and F1 layer (Pezzopane and Scotto, 2008) were added to extend and improve the functionality of Autoscala. Additionally, to extract more accurate values of the F2 layer, Scotto and Pezzopane (2008) and Pezzopane and Scotto (2010) have made elaborate efforts in the procedure of Autoscala.

Recently, Jiang et al. (2013) proposed an automatic scaling technique for obtaining the F2 parameters and F1 critical frequency from vertical incidence ionograms. The ionogram autoscaling technique based on the template matching method uses the Quasi-Parabolic Segments (QPS) to model the electron density profile. First, the proposed technique builds candidate electron density profiles based on International Reference Ionosphere (IRI) (Bilitza, 1990, 2001; Bilitza and Reinisch, 2008; Buresova et al., 2009) for ionograms. Then, the corresponding candidate traces are calculated using the corresponding electron density profiles. To reduce the matching time, Empirical Orthogonal Functions (EOFs) are used to build a new model that can decrease the size of the

* Corresponding author.
E-mail address: chuajiang@whu.edu.cn (C. Jiang).

http://dx.doi.org/10.1016/j.jastp.2015.09.002
1364-6826/

candidate traces. However, to be capable of autoscaling of ionograms recorded at different locations, the autoscaling technique proposed by Jiang et al. (2013) requires building different candidate traces.

In this work, the simulated annealing (SA) algorithm is applied instead of EOFs to reduce the matching time between candidate traces and recorded ionograms. As well known, the SA algorithm is an optimization algorithm for searching best-fit parameters in a big solution space. Due to rapidly searching best-fit parameters for the matching procedure in the autoscaling technique, various candidate traces are not necessary to be built for ionograms recorded at different locations. Therefore, we just evaluate the initial parameters of QPS model and the corresponding range of parameters. Then, the SA algorithm is applied to search the best-fit parameters of QPS model for recorded ionograms in the solution range of parameters.

In the following paragraphs, we first describe how the simulated annealing algorithm is applied in the autoscaling technique (Jiang et al., 2013). Then, ionograms recorded at different geographic locations are used to test the performance of the improvement in the presented study. Finally, conclusion related to the presented improvement is summarized.

2. Simulated annealing algorithm

Simulated annealing was first proposed by Kirkpatrick et al. (1983) for finding the minimum of a given function depending on many parameters named combinatorial optimization. Since then, the simulated annealing algorithm is applied in various fields. Rothman (1986) first introduced the simulated annealing to the inversion of geophysical problem. Benito et al. (2008) implemented inversion of backscatter ionograms optimization by simulated annealing and genetic algorithms. Song et al. (2011) carried out inversion of HF sweep-frequency backscatter ionograms using simulated annealing. Results of Song et al. (2011) show that this algorithm can give accurate inversion values rapidly. In the simulated annealing algorithm, the objective function, the acceptance probability, and the perturbation function need to be determined.

In this study, the objective function is related to the template matching algorithm. A recorded ionogram can be represented by a two-dimensional matrix A (M, N), where M is the number of the frequency points and N is the number of the virtual height points. A synthesized trace also can be represented by a two-dimensional matrix B (M, N), where M and N are same as the matrix A (M, N). Thus, we obtain the best-fit trace of the recorded ionogram using Eq. (1). When the value of Eq. (1) is the maximum, the corresponding trace is considered to be the best-fit trace. Then, the corresponding parameters of QPS model are considered to be optimization values.

$$F = \sum_{i=1,j=1}^{M,N} A(i,j)*B(i,j), \;\; where\; i \le M, j \le N \tag{1}$$

where M is the number of the frequency points and N is the number of the virtual height points, A and B represent a recorded ionogram and a synthesized trace, respectively. However, value of the objective function should be the minimum value for combinatorial optimization in simulated annealing algorithm. Thus, Eq. (1) is replaced with Eq. (2) to be the objective function of the simulated annealing in this study.

$$\sigma_p = 1/F \tag{2}$$

The perturbation function proposed by Ingber (1989) is applied in the presented work. However, the perturbation function is

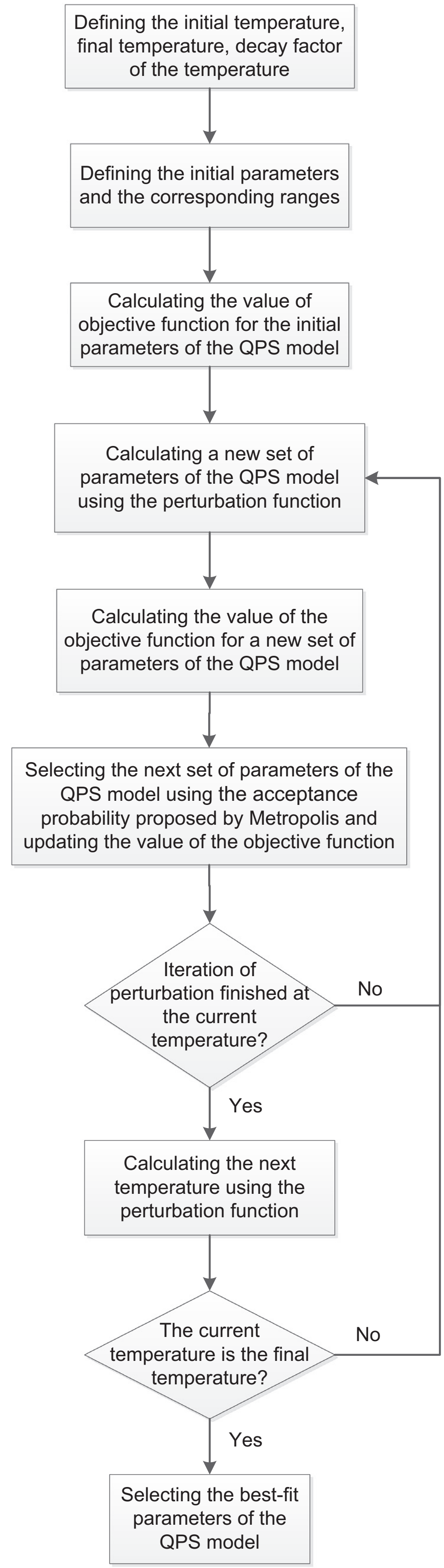

Fig. 1. The flowchart of the simulated annealing algorithm for automatic scaling of ionograms.