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Automatic interpretation of oblique ionograms

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Abstract

We present an algorithm for the identification of trace characteristics of oblique ionograms allowing determination of the Maximum Usable Frequency (MUF) for communication between the transmitter and receiver. The algorithm automatically detects and rejects poor quality ionograms. We performed an exploratory test of the algorithm using data from a campaign of oblique soundings between Rome, Italy (41.90 N, 12.48 E) and Chania, Greece (35.51 N, 24.01 E) and also between Kalkarindji, Australia (17.43 S, 130.81 E) and Culgoora, Australia (30.30 S, 149.55 E). The success of these tests demonstrates the applicability of the method to ionograms recorded by different ionosondes in various helio and geophysical conditions.

Keywords: Ionosphere; Electron density; Oblique ionograms; MUF

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1. Introduction

The variable state of the ionosphere is generally monitored by networks of vertical ionosondes, providing real-time information on the state of the ionosphere. An oblique ionospheric sounder extends this concept: the transmitter and receiver of an oblique sounder are not co-located, unlike vertical sounders, and are generally several hundreds or thousands of kilometers apart, so that the instrumentation is able to study how High Frequency (HF) radio signals propagate via the ionosphere under a variety of conditions.

For vertical ionograms there are well-established techniques that make it possible to obtain the main physical parameters of the ionosphere in real-time. These include the ARTIST system (Reinisch and Huang, 1983; Gilbert and Smith, 1988; Galkin et al., 2008) developed at the University of Lowell, Center for Atmospheric Research, and the Autoscala program from the Italian “Istituto Nazionale di Geofisica e Vulcanologia (INGV)” (Scotto and Pezzopane, 2002; Pezzopane and Scotto, 2007; Scotto, 2009). The data produced by these computer programs can be effectively integrated in real-time and short term forecasting models (Galkin et al., 2012). However, the interpretation of oblique ionograms is significantly more complex, and there are no well established automatic techniques.

The reason for the lack of such techniques is partly due to the relatively rare use of this type of sounding, at least in a systematic way, with the consequence of less effort being dedicated to them. Undoubtedly, it is also due to the

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greater difficulties that these ionograms pose compared to vertical soundings. On the other hand, the information obtained from an oblique HF sounder is much more articulated than that derived from traditional vertical ionogram readings. Noteworthy in this respect are the attempts of Huang et al. (1996) to develop a computationally efficient technique for the inversion of oblique ionograms, in order to obtain mid-point electron density profiles.

The reason that the inversion of an oblique ionogram is much more difficult than the inversion of a vertical one is because an obliquely propagating radio wave is refracted and not just reflected, making it far more prone to the effects of horizontal gradients and variations in the ionosphere, and posing significant problems for ray-tracing (Norman and Cannon, 1999). The situation is further complicated by the fact that radio signals from a transmitter can take a variety of different paths to reach the receiver, adding possible sources of signal distortion and loss.

Oblique ionograms provide high-resolution images that permit quick identification of the frequencies that are propagating between given transmitter and receiver stations. They also reveal the available communication bands and the gaps where no links can be established. These characteristics of a channel are very important because the information on available frequencies needs constant update, considering that the ionosphere changes on a time scale of every few minutes.

In the absence, until now, of software for automatic interpretation, oblique soundings have largely been used to try to understand the factors aggravating propagation in order to reduce radio link unreliability produced by natural ionospheric variability. Oblique ionospheric sounding also offer several important advantages over vertical sounding for the understanding of radio wave propagation. For example the possibility to monitor the ionosphere across large otherwise inaccessible distances, like the oceans.

The greater complexity of oblique compared to vertical ionograms is matched by greater informational content, affording to this technique enormous potential, which, in the opinion of the authors, has not yet been fully exploited. It is perfectly reasonable to presume that ionospheric structure can be determined from an oblique ionogram, albeit with much greater difficulty than from a vertical ionogram.

2. An algorithm for the automatic scaling of oblique ionograms

The software developed in this study, initially stores an ionogram as a matrix A, with m rows and n columns, as defined by the following formulas:

$$m = int\left[\frac{t_f - t_0}{\Delta_f}\right] + 1, \tag{1}$$

and

$$n = int\left[\frac{f_f - f_0}{\Delta_f}\right] + 1, \tag{2}$$

where f_f, f_0, Δ_f, t_f, t_0, Δ_t, are respectively the final frequency, the initial frequency, the frequency step, the final time delay, the initial time delay, and the time delay resolution of the oblique sounding. In general, t_0, Δ_t are fixed values, which depend on the design of the ionosonde. The transmitting system is based on a VOS-1 chirp ionosonde produced by the Barry Research Corporation, Palo Alto, CA, USA [Barry Research Corporation, 1975] sweeping from 2 to 30 MHz at 100 kHz/s with an average power of less than 10 W. The transmitting antenna is a delta for decametric wavelength used for vertical soundings, suited for oblique soundings. The receiver is an RCS-5B chirp produced by the Barry Research Corporation (1989). The element a_{ij} (with $i = 1, \ldots, m$ and $j = 1, \ldots, n$) of the matrix A is an integer ranging from 0 to 255 proportional to the amplitude of received echo, this value being obtained directly from the binary file recorded by the instrument.

Once the ionogram is stored in the form of a matrix of elements a_{ij}, two empirical curves s_{ord} and s_{ext} are defined, each of which is the branch of a parabola. These two curves are able to fit the typical shapes of the ordinary and extraordinary oblique ionogram traces resulting from a single reflection in the F2 region. The curve s_{ord}, which is used for the investigation of the ordinary trace, is:

$$t_{\mathrm{ord}} = \mathrm{int}\left[A_{\mathrm{ord}} f^2 + B_{\mathrm{ord}} f + C_{\mathrm{ord}}\right], \tag{3}$$

where f varies within the limits:

$$f_{\mathrm{v\_ord}} - \delta_{\mathrm{f\_ord}} \leqslant f \leqslant f_{\mathrm{v\_ord}}. \tag{4}$$

The coefficients A_{ord}, B_{ord}, and C_{ord} are related to $f_{\mathrm{v\_ord}}$, $\delta_{\mathrm{f\_ord}}$, $t_{\mathrm{v\_ord}}$, $\delta_{\mathrm{t\_ord}}$ by the following relationships:

$$A_{\mathrm{ord}} = -\frac{(\delta_{\mathrm{f\_ord}} - f_{\mathrm{v\_ord}})}{\delta^2_{\mathrm{t\_ord}}} - \frac{f_{\mathrm{v\_ord}}}{\delta^2_{\mathrm{t\_ord}}}, \tag{5}$$

$$B_{ord} = \frac{2(\delta_{\mathrm{f\_ord}} - f_{\mathrm{v\_ord}}) \cdot t_{\mathrm{v\_ord}}}{\delta^2_{\mathrm{t\_ord}}} + \frac{2 \cdot f_{\mathrm{v\_ord}} \cdot t_{\mathrm{v\_ord}}}{\delta^2_{\mathrm{t\_ord}}}, \tag{6}$$

and

$$C_{ord} = -\frac{(\delta_{\mathrm{f\_ord}} - f_{\mathrm{v\_ord}}) \cdot t^2_{\mathrm{v\_ord}}}{\delta^2_{\mathrm{t\_ord}}} + \frac{f_{\mathrm{v\_ord}} \cdot \left(\delta_{\mathrm{t\_ord}}{}^2 - t^2_{\mathrm{v\_ord}}\right)}{\delta^2_{\mathrm{t\_ord}}}. \tag{7}$$

Similarly, for the curve s_{ext}, used for the investigation of the extraordinary ray:

$$t_{\mathrm{ext}} = \mathrm{int}[A_{\mathrm{ext}} f^2 + B_{\mathrm{ext}} f + C_{\mathrm{ext}}], \tag{8}$$

where f varies within the limits:

$$f_{\mathrm{v\_ext}} - \delta_{\mathrm{f\_ext}} \leqslant f \leqslant f_{\mathrm{v\_ext}}. \tag{9}$$

The coefficients A_{ext}, B_{ext}, and C_{ext} are related to $f_{\mathrm{v\_ext}}$, $\delta_{\mathrm{f\_ext}}$, $t_{\mathrm{v\_ext}}$, $\delta_{\mathrm{t\_ext}}$ by the following relationships: