Journal of Atmospheric and Solar-Terrestrial Physics 121 (2014) 89–97

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Guided radio-wave propagation in the equatorial ionosphere according to the topside sounding onboard Interkosmos-19

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ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form
29 September 2014
Accepted 2 October 2014
Available online 23 October 2014

Keywords:
Waveguide propagation
Topside sounding
Equatorial ionosphere
Intercosmos-19

ABSTRACT

In addition to normal vertical-incident ionogram traces, strongly remote (up to 2000 km) traces of HF-radio-signal reflections observed on topside-sounder ionograms of the Interkosmos-19 satellite obtained in the equatorial ionosphere are presented. Such traces are connected with waveguides (ducts). These waveguides are field-aligned irregularities of the ionospheric plasma with electron density depletions of a few percent and cross-field dimension of a few to several kilometers. Ray tracing confirms this supposition and allows an estimate of typical waveguide parameters: diameter ≤ 10–15 km and amplitude $|\Delta N/N| \geq 10\%$, where N is the electron density. The waveguide traces usually start at the cutoff frequencies of the main traces. However, sometimes they begin at much lower frequencies which indicates the satellite was transitioning through an equatorial plasma bubble during the recording of the ionogram. The *X*-mode of ducted echoes is more distinct then the *O*-mode. Only one ducted trace is usually observed on the Interkosmos-19 ionograms; a second conjugate trace is rarely recorded. The same is true for combination modes which is a combination of an oblique-incidence and guided propagation. Waveguides are observed at all heights of Interkosmos-19 (500–1000 km) inside the equatorial anomaly region (from $-40°$ to $+40°$ Dip). Waveguides are usually associated with other irregularities of various sizes in the equatorial ionosphere, some of which cause additional traces and spread *F* on the topside-sounding ionograms. Ducted-echo characteristics observed with Interkosmos-19 are different from those observed earlier with the Alouette and ISIS satellites. This difference is discussed. It is shown that the ionospheric plasma irregularities responsible for the waveguides are observed much more often during nighttime than during daytime.

1. Introduction

The Interkosmos-19 (IK-19) satellite data were recently retrieved. It was found that on the IK-19 topside-sounder ionograms recorded in the equatorial ionosphere additional remote traces are often observed. They usually start at the cutoff frequencies of the main traces and occasionally at much lower frequencies. They usually start at the satellite height and then extend over large apparent ranges up to the 2000-km limit of the IK-19 ionogram. Only one remote trace is usually observed on the IK-19 ionograms; conjugate traces (echoes from the opposite hemisphere) are rarely observed. Conjugate traces are observed at very large apparent ranges. The *X*-mode of the remote echoes is always more distinct then the *O*-mode. For the *X*-mode the apparent (virtual) range of these traces always increases as the satellite moves toward the magnetic equator since the satellite is moving away from the reflection area. This indicated MF- and HF-radio wave propagation in waveguides (Muldrew, 1963, 1967, 1969). The waveguides are field-aligned plasma irregularities with depleted electron density relative to the background level. The observed traces can be distinct and clear even if the main (i.e., vertical incidence) traces are strongly diffuse due to spread *F*. Therefore the remote traces are not scattered by multiple irregularities because they would also be diffuse. This feature is an inherent property of waveguides probably because their walls have to be smooth; otherwise the signal would be scattered and may not return to the satellite. Sometimes remote traces were recorded on a series of successive ionograms. However, they are usually recorded discontinuously, i.e., not on each ionogram as the satellite crossed the equator. Moreover, an additional trace can be recorded completely or partially in a narrow range of frequencies, i.e., in a small time range. This also indicates the waves are trapped in waveguides since the signals are only received when the satellite is inside the waveguide. In the

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http://dx.doi.org/10.1016/j.jastp.2014.10.008
1364-6826/

case of reflection from a large-scale irregularity the trace would be completely observed on several ionograms. Thus, the features of additional remote traces suggest that they are associated with guided MF and HF wave propagation. Hence, this hypothesis is carefully tested among other possibilities. The main goal of this work is to test this hypothesis using ray tracing and to determine the parameters of the waveguides. Waveguide propagation was also observed on the Alouette and ISIS ionograms (Muldrew, 1963, 1967, 1969; Dyson, 1967; Ramasastry and Walsh, 1969; Hagg et al., 1969; Ramasastry, 1971; Dyson and Benson, 1978; Gross and Muldrew, 1984; Benson, 1985; Calvert, 1995). However, their characteristics are very different from the characteristics described above. The main difference is that on the Alouette/ISIS ionogram the whole family of guided traces connected with multiple reflections from the dense ionosphere in both hemispheres could be observed. The Alouette/ISIS satellites recorded ducted signals without strong attenuation at apparent distances over 12,000 km, while the IK-19 satellite recorded traces at apparent distances only up to 2000 km. Also, the guided traces on the Alouette/ISIS ionograms were observed at much lower frequencies (usually below 3–4 MHz and rarely up to 6–7 MHz) than the guided traces on the IK-19 ionograms (from 3 up to 16 MHz). Therefore, the second goal of the present study is to discuss and explain these differences.

2. Dayside ionosphere

2.1. Interkosmos-19 data

The IK-19 satellite operated in a period of high solar activity ($F_{10.7}$=150–250) from March, 1979 till March, 1981. It had an elliptical orbit of 500–1000 km with an inclination of 74°. The satellite could record digital ionograms with intervals of 16 and 64 s. Below, two sounding sessions in a day-time and night-time ionosphere are considered, that were carried out with an interval between ionograms of 16 s, which corresponds to about of 120 km in horizontal distance. The time for one ionogram recording was 6 s. During this time the ionosonde sweeps a frequency range from 0.3 to 15.95 MHz. During the transmitter operation period of 133 μs the receiver was switched off and the radio signal reflections on the IK-19 ionograms started at the apparent distance of 80 km. It is important to note that due to an insufficiently large storage memory on board the satellite the ionosonde recorded only the three strongest radio signal reflections on each frequency. As a result, noise can shield the useful signal.

In Fig. 1 the ionogram recorded in the day-time (11:15 LT) equatorial ionosphere on April 2, 1979 is shown. It is characterized by the strong remote traces at apparent ranges larger than the main-trace apparent range (more than 1600 km at the highest

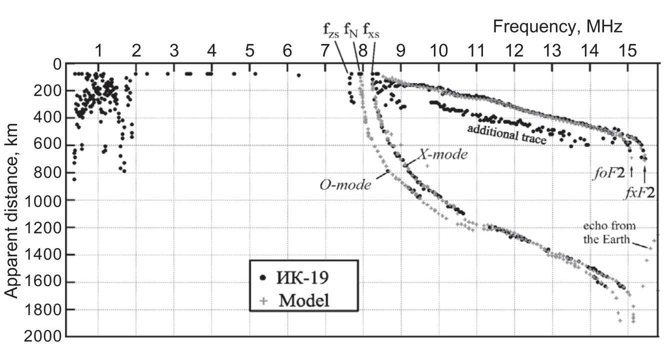

Fig. 1. IK-19 ionogram recorded on April 2, 1979 at 11:57:37 UT (11:15 LT) at 1.5°N (−11°*I*), 347.7°E, and 746 km altitude with f_h=0.58 MHz, and f_N=7.95 MHz. A model ionogram, designated by crosses (see discussion in Section 2.2) is superimposed on the experimental one.

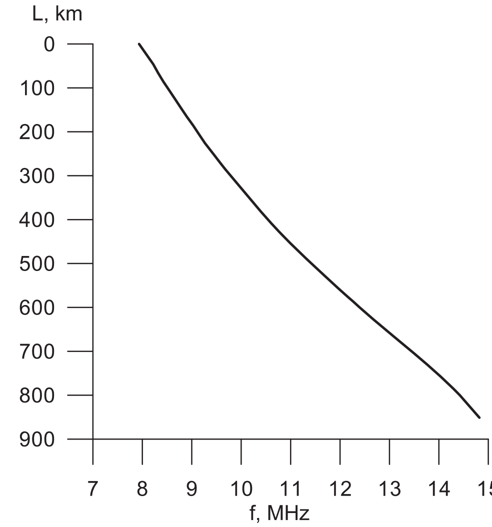

Fig. 2. $f_N(L)$-profile for the waveguide trace in Fig. 1.

frequencies). The remote traces are clearly seen without large scattering. The extraordinary mode is recorded completely, up to the critical frequency, and the ordinary mode is represented by separated fragments. This is typical for the additional remote traces. The extraordinary trace starts at the cutoff frequency of the main trace (f_{xs} ~8.25 MHz). The echo near 9 MHz and 300 km and the additional trace below and almost parallel to the main trace are evidently the combination modes first described by Muldrew (1963) and since discussed by others (see, e.g., Dyson (1967) and Gross and Muldrew (1984)). These modes are created by waves which initially propagate slightly obliquely and are then trapped in a duct or ducts near the reflection height.

Fig. 2 shows the $f_N(L)$-profile calculated for the waveguide trace *X*-mode assuming the radio signal propagating along the field line, i.e., along the waveguide axis. The laminar Jackson's method is used to calculate the topside *N(h)*-profiles (Jackson, 1969). The field line is calculated using the Tsyganenko model (http://geo.phys.spbu.ru/~ tsyganenko/modeling.html). The distance L_m from the satellite to the signal penetration level at the height h=$hmF2_{WG}$ for the waveguide-trace critical-frequency, $foF2_{WG}$ =14.8 MHz, is 850 km. The $hmF2_{WG}$ will be defined below.

Fig. 3 shows the scheme of the experiment on April 2, 1979. In the middle panel the *foF*2 latitudinal variations are given. Since the local time at the equator was 11:15 h the equatorial anomaly was yet poorly developed. The latitudinal variations in *F*2-layer height are shown in the bottom panel. They are typical for this local time; *hmF*2 is a maximum near the equator. The same plot shows two geomagnetic field lines that pass through the points in the orbit where the waveguide traces were recorded. It is seen that a ducted trace was recorded not only in the southern hemisphere (see ionogram in Fig. 1 corresponding to point 2 in the upper panel of Fig. 3), but in the northern hemisphere (in the geomagnetic latitude frame) as well. (The ionogram in the northern hemisphere, corresponding to point 1 in the upper panel of Fig. 3, does not practically differ from the ionogram in Fig. 1.) In the top panel the dashed line shows the orbit projection for the given IK-19 path, solid lines show the magnetic field lines passing through the sounding region. Both ducted traces were observed at very close magnetic inclinations, namely 11–12°, but they were on different *L* shells and at different longitudes.

It is 850 km along the field line in the southern hemisphere from the satellite to the penetration point in the waveguide at the critical frequency $foF2_{WG}$=14.80 MHz. The height $hmF2_{WG}$ is about 450 km at latitude of about 4.9°S (marked by a point along one of