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Compatible analysis of vertical and oblique ionospheric sounding data

Igor V. Krasheninnikov (1), **Jean-C. Jodogne** (2) and **Luis F. Alberca** (3)
(1) *Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Troitsk, Moscow Region, Russia*
(2) *Institute Royal Meteorologique, Bruxelles, Belgium*
(3) *Observatory de l'Ebre, Roquetes, Tarragona, Spain*

Abstract
Examples are presented of the ray-tracing synthesis of multifrequency Oblique Sounding (OS) data on the Dourbes (Belgium) – Roquetes (Spain) path using electron density height profiles derived from Vertical Sounding (VS) measurements at both terminals. Comparison with the measured OS ionograms provides a means of assessing the accuracy of the VS true-height procedure POLAN. Particular attention was paid to a consideration of the E-F_1 valley, that as concluded is often less deep than currently supposed, when derived using both ordinary and extraordinary components of the VS ionograms. Also, it was found that the peak of the F_1 -layer should be expressed more distinctly (sometimes with a small valley between the F_1 and F_2 layers) though the corresponding VS ionograms may have no discontinuity in the region.

Key words *ionosphere – VS and OS ionograms – OS ionogram synthesis – ray-tracing technique*

1. Introduction

OS ionograms show the group delay dependence over a defined frequency range. This group delay function depends upon the ionospheric structure in a much more complex way than for VS. For instance, whereas the critical frequencies on VS ionogram depend only on the plasma frequencies of the different layer peaks, specific points on OS ionograms such as the Junction Frequency (JF) are dependent not only upon these characteristics but also on the form of the height distribution of electron density and to a considerable degree on the extent of horizontal inhomogeneities over the path. In this regard it is interesting to analyze simultaneous OS and VS measurements collected at the end points of the path in order not only to establish their mutual dependence, but more importantly to find possible ways of increasing the accuracy of real-height profile estimation. In this paper some results of such analysis are presented for the 1120 km path Dourbes – Roquetes with emphasis on an investigation of the height intervals between the different layers.

2. OS ionogram synthesis

An important part of the analysis is a technique of OS ionogram synthesis based on the equations of Haselgrove (1954) in a form when

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Mailing address: Dr. Igor V. Krasheninnikov, Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Troitsk, Moscow Region, 142092 Russia; e-mail: krash@charley.izmiran.rssi.ru

an argument of the equations is real time (Kravtsov and Orlov, 1990):

$$\frac{d\vec{r}}{dt} = \frac{\vec{k} - \dfrac{\omega^2}{2c^2}\dfrac{\partial \mu^2}{\partial \vec{k}}}{\dfrac{\omega\mu}{c^2}\dfrac{\partial(\omega\mu)}{\partial\omega}} \qquad \frac{d\vec{k}}{dt} = \frac{\dfrac{\omega}{2\mu}\dfrac{\partial \mu^2}{\partial \vec{r}}}{\dfrac{\partial(\omega\mu)}{\partial\omega}} \tag{2.1}$$

$$\vec{r}(0) = \vec{r}_t \qquad \vec{r}(t_g) = \vec{r}_r$$

where $\vec{r}$ – radius and $\vec{k}$ – wave vectors, ω – radian frequency of current radiated wave, c – velocity of light in free space, t – time delay, ct – group delay in current point of the trajectory, $\vec{r}_t$ and $\vec{r}_r$ – coordinates of terminals. Refractive index μ was taken in form of the Appleton – Lassen formula when its imaginary part is much lower than the real one (Budden,1961; Davies,1969)

$$\mu^2(\vec{r}, \vec{k}, \omega, \theta) = 1 - \frac{2X(1-X)}{2(1-X) - Y^2\sin^2\theta \pm \sqrt{D_1}} \tag{2.2}$$

$$D_1 = Y^4\sin^4\theta + 4Y^2(1-X)^2\cos^2\theta,$$
$$Y = \omega_H/\omega, \qquad X = \omega_N^2/\omega^2$$

where ω_H – radian gyrofrequency, ω_N – radian plasma frequency and θ – the angle between wave's and Earth's magnetic field vectors. Signs «+» and «–» correspond to ordinary and extraordinary components of the wave, respectively. The pair (f, ct_g) is one point of the synthesized OS ionogram.

In the ray-tracing method implementation the Earthed-centered dipole magnetic field model was used. Electron-density height profile was assumed to vary linearly with distance along the great-circle path and to be given from three separate versions of the true-height analysis procedure POLAN (Titheridge, 1988) applied to the two terminal VS measurements. No attempt was made to simulate transmission losses at the different frequencies in eq. (2.1) but some such estimates for the isotropic case were performed for true-height profiles from VS data and frequency collision profiles from IRI ionospheric model on the path (Krasheninnikov *et al.*, 1993).

3. Results

Figure 1a,b gives sample summer daytime VS ionograms recorded at Dourbes and Roquetes respectively at 1400 UT on 21 June 1992 and fig. 1c shows the corresponding OS ionogram measured at nearby time. The OS ionogram shows the classical JF's of the high and low-angle ray traces for the F_1 and F_2 layers. Because of sensitivity limitations of the equipment the high-angle ray trace for the E-layer is nearly always absent so that a JF determination is not a simple problem. In this example, no E_s – traces were observed at the VS ionograms and consequently one can consider MOF (Maximum Observable Frequency) for the layer as its JF.

Figure 2a-f gives the corresponding true-height profiles (curves for Dourbes and Roquetes are marked by «D» and «R» and the last ones are displaced for clarity by 1 MHz) and the results of the OS ray-tracing simulations. In fig. 2a an E-F_1 valley is assumed as determined from the simultaneous analysis of the ordinary and extraordinary wave components. Figure 2c has a less-deep valley based on analysis of the ordinary wave trace alone with a valley width equal to the initial default value of twice the scale height for the E-layer. The valley is absent in fig. 2e. Corresponding OS synthesized ionograms are presented in fig. 2b,d,f. It is seen in comparison with the measured OS ionogram of fig. 1c that, despite the quite strong horizontal gradient of electron concentration along the path, measured and synthesized $1F_2$ mode JF's agree well to within 0.1 MHz in all cases. The same is true for the E layer JF's although height profiles for the layer slightly differ. However, for the F_1 mode JF there are important differences, reflecting the fact that the mode trace depends to a considerable degree on the form of the height distribution between the E and F_1 layers. Calcu-

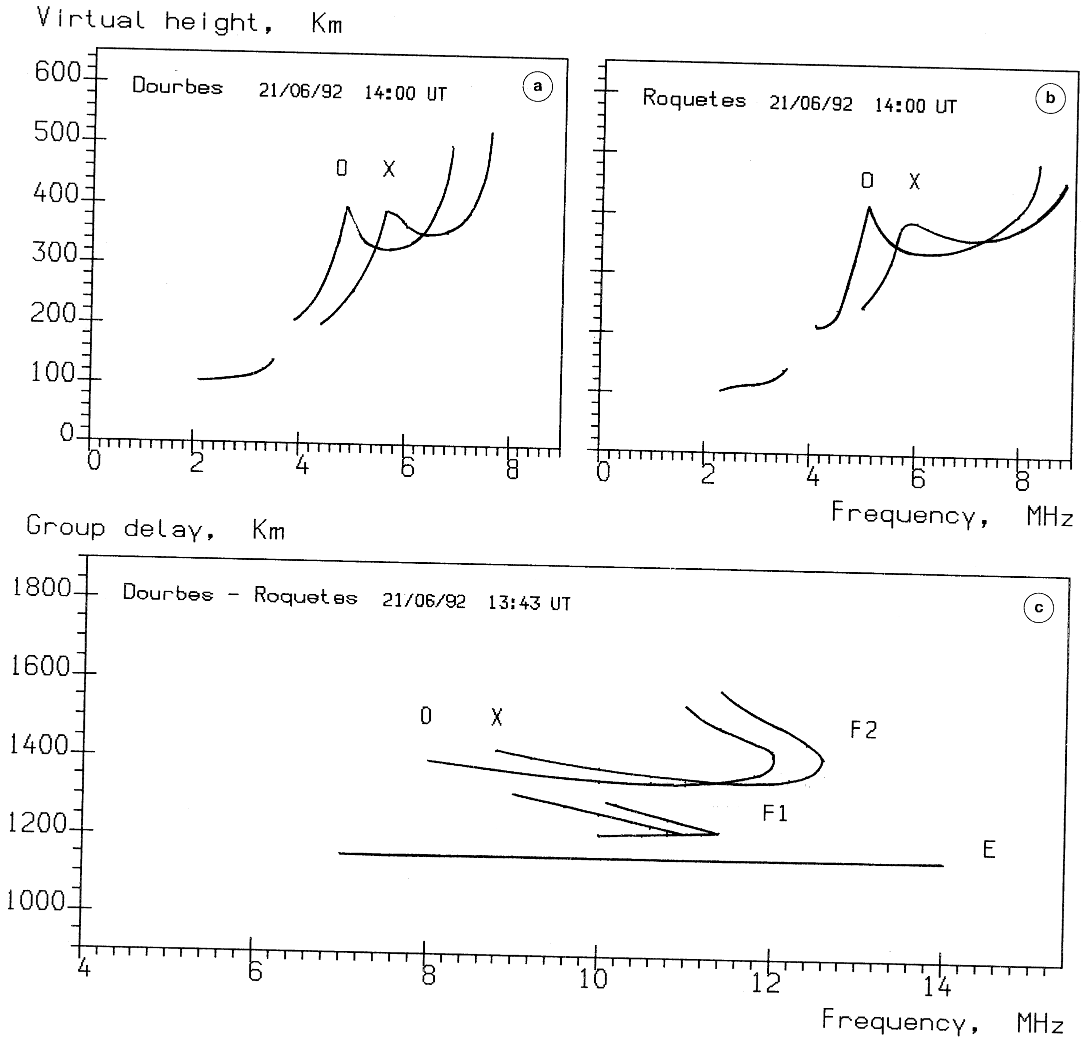

Fig. 1a-c. An example of sounding: vertical (a,b) and oblique (c) on the Dourbes-Roquetes path.

lated extraordinary wave $1F$ mode JF's range from 11.2-12.0 MHz in comparison with the experimental value of 11.4 MHz. The valley structure is also seen to influence significantly the group delays of the low-angle F_1 mode and the frequency it starts from, F_1 mode propagation being more significant the deeper the valley.

There is a somewhat similar situation in the interval between the F_1 and F_2 layers. The low-angle ordinary-wave trace is seen on the OS ionogram to start at a frequency of 8 MHz whereas in the simulations the trace starts some 1 MHz higher in frequency. It is recognized that the ray-tracing results are influenced by the computation frequency step size but in this region it is considerably less than 1 MHz (about 0.1-0.2 MHz). It means that there are evident differences which, following the previ-

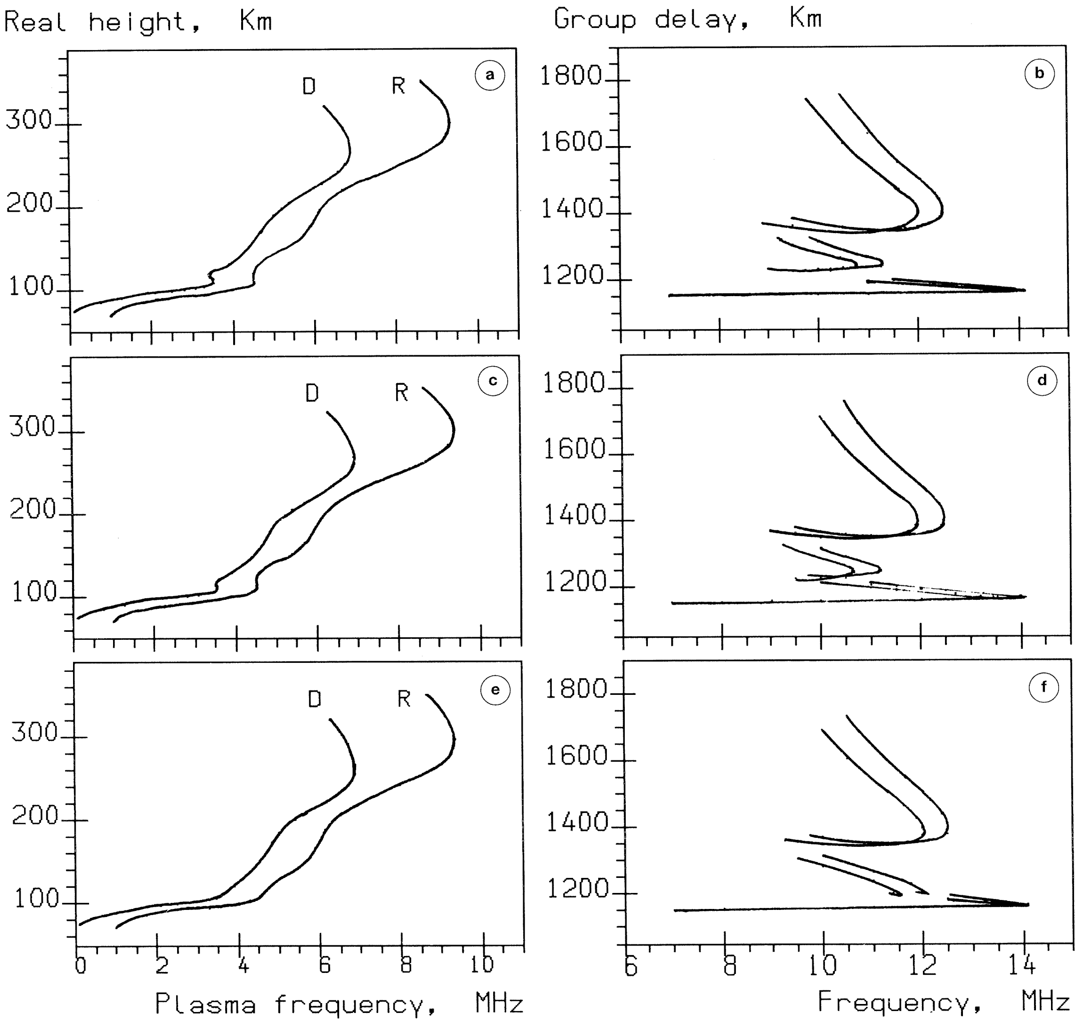

Fig. 2a-f. A sequence of $N(h)$-profiles (a,c,e), derived from VS ionograms by POLAN program, and corresponding synthesized OS ionograms (b,d,f). VS profiles for Roquetes are shifted by 1 MHz.

ous results, suggest that the F_1 layer should have a more clearly developed peak. It might even be possible that a small valley exists between the F_1 and F_2 layers, not shown by the POLAN results or discernible from the VS ionograms.

Another example of such analysis is presented in fig. 3a-e for data recorded at 1143 UT on 15 September 1992. Figure 3a shows the measured ionogram. In contrast to the previous case there is now no JF for the F_1 layer, *i.e.*, its low-angle branch is absent. Corresponding estimations of real height profiles at the terminal points and the synthesized OS ionograms are shown in fig. 3b,c, when POLAN determined valleys using both ordinary and extraordinary components. In fig. 3d,e, it is assumed that no valley exists. As in the previous case, one can see a close coincidence of calculated and experimental JF's for the *E* and F_2 layers in both sets of height profiles. There is a clear dependence of the F_1 traces on the form of the profiles – the no valley profiles evidently explain the shape of the traces better than the valley profiles and calculate better MOF's and group delay values. By removing the 15 km valley at Dourbes and the 33 km valley at Roquetes, the F_2 peak heights are lowered by 5 km at Dourbes and 7 km at Roquetes.

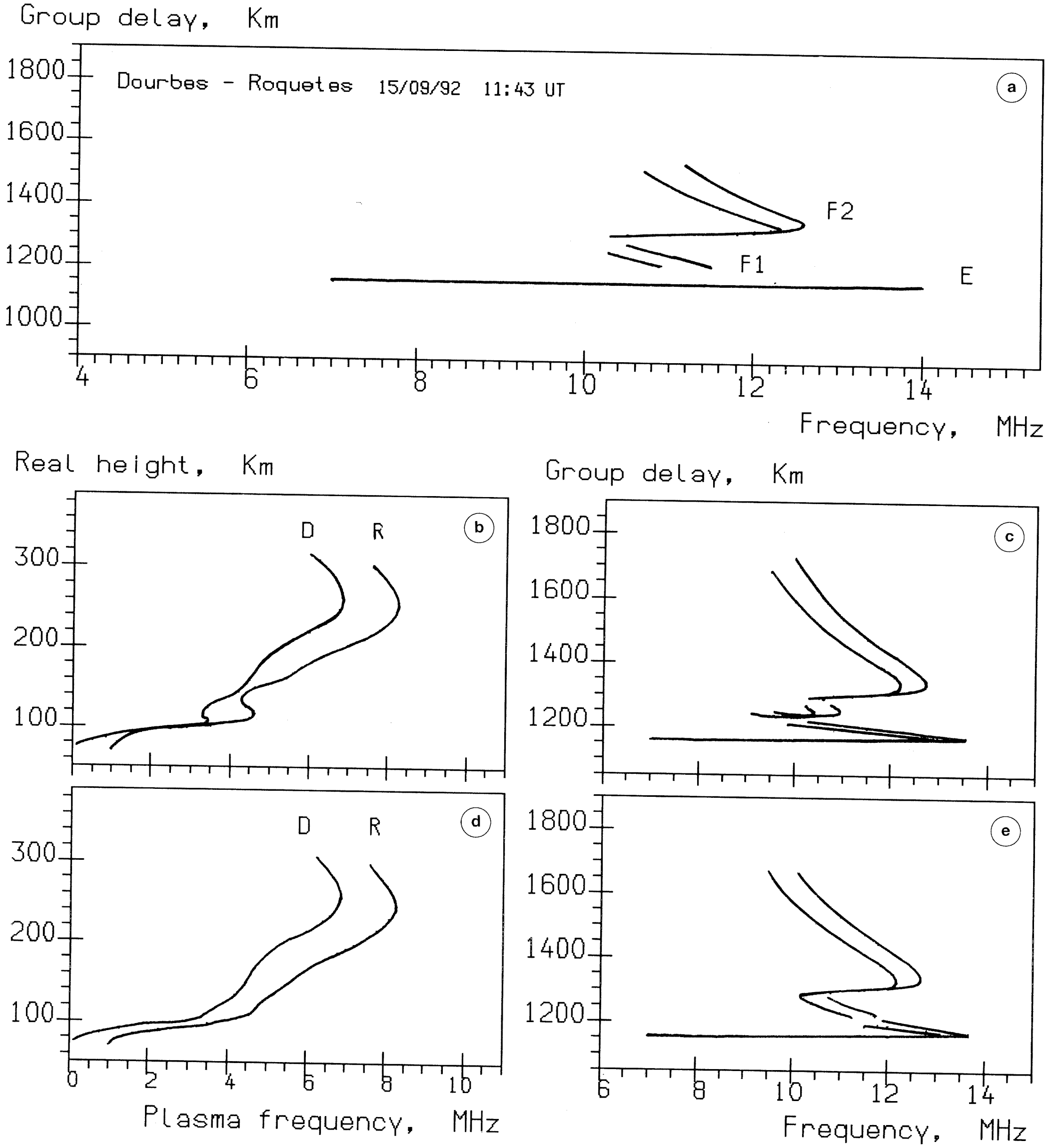

Fig. 3a-e. Experimental (a) and simulated (c,e) on profiles (b,d) OS ionograms.

4. Conclusions

Compatible analysis of VS data involving ray-tracing simulations offers a potential for developing an operational technique for electron-density profile valley determination.

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REFERENCES

BUDDEN, K.G. (1961): *Radio waves in the ionosphere* (Cambridge University Press, New York).

DAVIES, K. (1969): *Ionospheric radio waves* (Blaisdell)

HASELGROVE, J. (1954): Ray theory and a new method for ray tracing. The physics of the ionosphere, *Phys. Soc., London*, 355-364.

KRASHENINNIKOV, I.V., J.-C. JODOGNE and L.F. ALBERCA (1993): On an interpretation of Dourbes-Roquetes oblique sounding data, in *Proceedings of PRIME COST 238 Workshop, Graz, Austria, 10-12 May 1993* (Institüt für Meteorologie und Geophysik, Karl-Franzes-Universität, Graz), **2/1993/Teil 2**, 329-334.

KRAVTSOV, YU.A. and YU.I. ORLOV (1990): *Geometrical optics of inhomogeneous media* (Springer, Berlin-Heidelberg-New York).

TITHERIDGE, J.E. (1988): The real height of ionograms: a generalized formulating, *Radio Sci.*, **23** (5), 831-849.