HF Propagation via the *F3* Layer

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ABSTRACT

An additional ionospheric layer, the F3 layer, has recently been identified in vertical incidence ionogram records from the equatorial station, Fortaleza in Brazil. This paper examines the HF propagation characteristics of this layer in the context of the signatures that would appear on backscatter and oblique ionograms. It is found that the relatively weak F3 layer reported at Fortaleza will not produce a pronounced signature on backscatter ionograms because the F3 layer produces mostly relatively weak echoes at the same ranges as much stronger F2 propagated echoes. In contrast, on oblique ionograms, F3 layer signatures are likely to be observed emerging from the high angle F2 trace. Of course if the F3 layer is pronounced enough then distinct echo traces occur on both backscatter and oblique ionograms.

1. INTRODUCTION

Recently Balan *et al.*, (1997, 1998) have shown that an additional layer, called the *F3* layer, can form in the equatorial ionosphere. In the late morning-noon period the upward drift produced by the combined effects of the **E** x **B** drift and neutral wind causes the *F2* layer to drift upwards, forming the *F3* layer, while the usual photochemical and dynamical effects maintain an *F2* layer at lower altitudes. Balan *et al.* (1997) presented bottomside ionograms from Fortaleza showing the presence of an *F3* layer in an ionogram sequence and later Balan *et al.*, (1998) presented occurrence statistics based on Fortaleza ionograms.

The presence of an *F3* layer may affect HF propagation so there are possible implications for communication and surveillance systems, such as the Jindalee Operational Radar Network (JORN). This paper presents the results of an initial theoretical investigation into the basic effects of an *F3* layer on HF propagation.

2. *F3* LAYER STRUCTURE

The *F3* layer can be identified by the appearance of an extra cusp on ionograms obtained by Vertical Incidence Sounders (VIS), as shown in the sequence of Fortaleza VIS ionograms presented by Balan *et al.*, (1997) [Figure 1]. However the identification may not be straightforward because travelling ionospheric disturbances (TIDs) and the *F1.5* layer (e.g. Rishbeth and Garriot, 1969) produce similar cusps. The ionograms in Figure 1 have been scaled and inverted using the POLAN method (Titheridge, 1985) to obtain vertical electron concentration profiles. The profile at 1130 LT is shown in Figure 2 and it is apparent that the *F3* layer is quite weak, with *foF3* being just slightly greater than *foF2*.

Balan et al (1997) modelled the *F3* layer using the Sheffield University plasmasphere-ionosphere model (SUPIM). They considered sunspot maximum conditions (F10.7 = 178) rather than the more moderate level of sunspot activity that prevailed at the time of the Fortaleza *F3* layer observations they presented (F10.7 = 78). Their modelling predicted the formation of an *F3* layer about an hour before noon and lasting several hours. However *foF3* was predicted to be smaller than *foF2* at times and a ground-based VIS will only detect the *F3* layer when *foF3* > *foF2*. At Fortaleza this occurs for typically 3 hours, although durations as short as 15 minutes and as long as 6 hours have been observed (Balan *et al.*, 1998).

The vertical electron concentration profile from the model results of Balan *et al.* (1997) is also plotted in Figure 2. It is taken from Balan et al, where the profile does not extend below 200 km, so in Figure 2 it has been extended using appropriate IRI parameters. The difference between the profile obtained from the ionogram inversion and the model profile is quite stark. The electron concentrations and heights of the *F2* and *F3* layers are much greater in the model case, which corresponds to higher solar activity.

3. IONOSPHERIC MODEL AND RAY TRACING

Oblique Incidence Sounders (OIS) and Back-Scatter Sounders (BSS) are used in systems such as the Jindalee Operational Radar Network (JORN) to monitor HF propagation conditions in real time and provide information for frequency management and target location, normally referred to as Coordinate Registration (CR). As explained above, the *F3* layer produces an identifiable signature on VIS ionograms and the aim here is to investigate what, if any, characteristic features will occur on OIS and BSS ionograms when *F3* layer propagation occurs. This has been pursued by specifying models of the ionosphere, including an *F3* layer, and using ray tracing to determine the corresponding OIS and BSS ionograms.

Our knowledge of *F3* layer behaviour is still very limited. Balan *et al.*, (1998) have completed a study of its occurrence at Fortaleza but there has been no study of its spatial extent. In fact one of the motivations of this study is to examine whether OISs and BSSs could readily contribute to morphological studies of the *F3* layer. In the absence of any real knowledge of the spatial extent of the *F3* layer, we confine our study to the effects of the vertical profile on oblique propagation. This is not as restrictive as might be first thought since, if the mid-point vertical profile is known, horizontal linear gradients have no first order effect on group path, the parameter displayed on VIS and BSS ionograms. Hence unless the *F3* layer produces highly non-linear horizontal structure, the use of a single vertical profile will be valid when applied to the mid-point of propagation paths. Hence it is applicable to OIS ionograms. In the case of BSS ionograms, no single mid-point profile is applicable, nevertheless, the use of a single vertical profile will highlight effects arising from the *F3* layer vertical structure.

We have synthesised OIS and BSS ionograms using the analytical ray tracing approach of Dyson and Bennett (1988), Chen *et al.* (1990) and Bennett *et al.*, (1991). Croft and Hoogasion (1968) showed that describing the ionosphere by a quasi-parabolic vertical profile gave rise to analytical solutions for ray parameters for propagation over a spherical Earth. Dyson and Bennett (1988) and Chen *et al.* (1990), extended this concept to the use of multi-quasi-parabolic segments to describe vertical profiles of arbitrary structure. In this approach the effect of the Earth's magnetic field on the propagation is generally ignored although it can be included (Chen *et al.*, 1992). The main effect of the Earth's magnetic field it to cause birefringence, so that on ionograms two echo traces are observed, corresponding to ordinary and extraordinary mode propagation. However these two traces generally exhibit similar characteristics so we can expect the *F3* layer to produce the same major effects on both traces. Hence we can safely ignore the Earth's magnetic field and hence birefringence.

OIS and BSS ionograms have been synthesized using the vertical profiles shown in Figure 2. While the profiles appear quite different, general features of the *F3* layer propagation are similar. The reason is related to the fact that, when the Earth's magnetic field is ignored, propagation effects scale as f/f_c where f is the propagation frequency and f_c is the maximum ionospheric plasma frequency (normally *foF2*, but in these cases *foF3*). The two profiles in Figure 1 are actually very similar in the *F2* and *F3* regions when they are normalised in this way (i.e. with f_c = *foF3*), and the heights, h, are also normalised using h/h_{max}, where h_{max} is the height of the *F3* layer peak. In both cases *foF2*/*foF3* is close to 0.90. Consequently we only show results for one case, viz., the SUPIM model profile of Figure 2

4. *F3* LAYER SIGNATURES ON BACK-SCATTER IONOGRAMS

For the ionospheric profiles shown in Figure 1, BSS ionograms have been synthesized using the general purpose analytical ray tracing package, QPSHEL (Dyson *et al.*, 1994). Since we are interested purely in the effect of the ionosphere on the propagation, and BSS system losses have been ignored and isotropic antennas have been assumed. The synthesised BSS ionogram for the SUPIM profile is shown in Figure 3.

It is apparent that the *F3* layer produces a relatively weak echo trace which is largely hidden behind the *E* and *F2* layer traces. This occurs because *foF3* is not much greater than *foF2* but at a greater altitude.

In a spherically stratified ionosphere Snell's Law become Bougere's Law and may be written as

$$r\,\mu\,\cos\beta = \text{const}$$

where r is the radial distance
μ is the refractive index
and β is the elevation angle at r.

$$\therefore\ r\,\mu\,\cos\beta = r_e \cos\beta_e$$

where r_e is the radius of the Earth
and β_e is the elevation angle at the Earth's surface.

At reflection a ray is horizontal, so

$$r_{\mathrm{R}}\,\mu_{\mathrm{R}} = r_e \cos\beta_e$$
$$\text{or}\ \ (\mu_{\mathrm{R}})^2 = (r_e \cos\beta_e / r_{\mathrm{R}})^2$$

Now,
$$(\mu_{\mathrm{R}})^2 = 1 - (f_n / f_{\mathrm{R}})^2$$
where f_n is the plasma frequency
and f_{R} is the radio propagation frequency reflected at r_{R}

Hence f_{RM}, the maximum value of f_{R} corresponds to the maximum value of μ_{R}, which occurs when $\cos\beta_e = 1$, i.e. when $\beta_e = 0$.

Figure 4 shows the variation of f_{RM} for the SUPIM profile. It is apparent that, consistent with the synthesised BSS shown in Figure 3, the *F2* layer can reflect higher frequencies than the *F3* layer. Of course the actual maximum frequencies reflected by each layer will be less than those shown in Figure 4 if the $\beta_e = 0$ and other low angle rays are reflected by lower layers. This is certainly true for the *F3* layer where the maximum frequency propagated by the layer is less than 31 MHz.

By way of contrast, a model vertical profile with a much more pronounced *F3* layer (Figure 5a) has also been used to synthesise a BSS ionogram. In this case a pronounced *F3* layer trace is produced (Figure 6) as would be expected from the plot of f_{RM} versus height (Figure 5b).

It is worth noting that because of the high altitude of the *F2* and *F3* layer peaks, both model ionospheres support single hop propagation over distances in excess of 6000 km.

5. THE *F3* LAYER OIS SIGNATURE

Figure 7 shows the oblique ionogram for a 1250 km path synthesised using the SUPIM profile. There is a distinct *F3* layer trace emerging from the high angle *F2* layer trace. Ionograms synthesised for other paths show a similar effect. This trace signature has been observed on OISs operating over paths extending north of Australia (Lynn, private communication). Such observations may be indications of the presence of an *F3* layer although this signature, of an additional layer trace emerging from the high angle *F2* layer trace, can also be produced by travelling ionospheric disturbances. From comparison of Figures 7 and 3 it is evident that the presence if a weak *F3* layer is more likely to be apparent on OIS ionograms than on BSS records.

The equivalent synthesised oblique ionogram for the more pronounced *F3* layer profile of Figure 5, is shown in Figure 8. In this case the *F3* layer is more pronounced, with three very obvious layer traces (E, *F2* and *F3*). In practice, the layers might be mistakenly identified as is E, F1 and *F2* or E, *F1.5* and *F2*. In a practical case it would be important to examine the time sequence of OIS ionograms, as is required for positive identification of *F3* layer from VIS ionograms. Comparison of Figures 8 and 6 shows that in this case the *F3* layer is clearly evident on both OIS and BSS ionograms.

6. CONCLUSIONS

The expected effects of the *F3* layer on OIS and BSS ionograms has been investigated by synthesising ionograms using model vertical profiles on the ionosphere. Two models have been used. One contains a weak *F3* layer, consistent with reported VIS observations and corresponding to an *F3* layer model developed by Balan *et al.,* (1997). The second model contains a pronounced *F3* layer.

If the *F3* layer is weak, then it is unlikely to be observed by BSS sounders because strong echoes propagated by lower layers (primarily the *F2* layer) will be superimposed on the weak *F3* layer echo trace. However the *F3* layer will be apparent on OIS ionograms as a trace emerging from the high angle *F2* layer trace and this is observed.

If the *F3* layer becomes pronounced enough so that it supports oblique propagation over long distances at higher frequencies than the *F2* layer, then very distinct traces may occur on both BSS and OIS ionograms. These traces exhibit the same distinct features displayed by traces caused by the other ionospheric layers. In principle the presence of an *F3* layer is then readily identifiable although in practice care will be required to avoid misidentification as an *F2* layer, followed by consequential misidentification of other layers.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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FIGURE CAPTIONS.

Figure 1. Sequence of VIS ionograms from Fortaleza (3^{o}S, 38^{o}W), showing presence of F3 layer (after Balan *et al.*, 1997).

Figure 2. Vertical ionospheric profiles at 1130 UT. Fortaleza profile obtained by inversion of corresponding ionogram in Figure 1. SUPIM profile adapted from Balan *et al.*, 1997.

Figure 3. (a) Backscatter ionogram synthesized using SUPIM profile from Figure 2.
(b) Layer traces displaced in group range.

Figure 4. Maximum frequency that can be reflected by the plasma frequency at a particular height.

Figure 5. (a) Vertical ionospheric profile.
(b) Maximum frequency that can be reflected by the plasma frequency at a particular height.

Figure 6. (a) Backscatter ionogram synthesized using profile from Figure 5(a).
(b) Layer traces displaced in frequency.

Figure 7. Oblique ionogram for SUPIM profile in Figure 2

Figure 8. Oblique ionogram for ionospheric profile in Figure 5

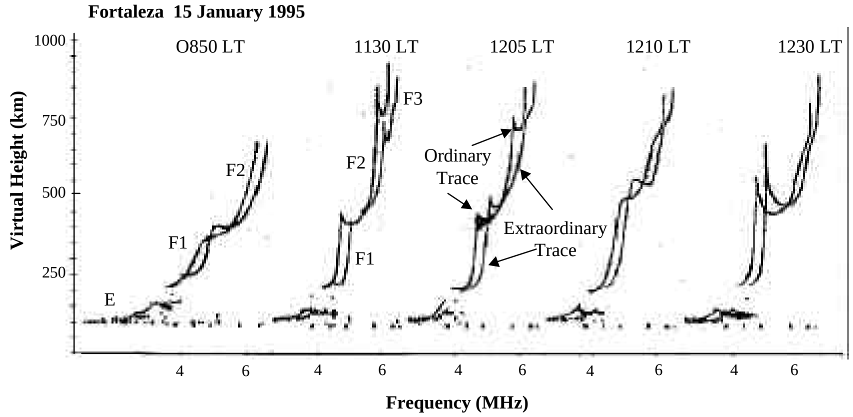

Figure 1. Sequence of VIS ionograms from Fortaleza (3^{o}S, 38^{o}W), showing presence of F3 layer (after Balan et al., 1997)

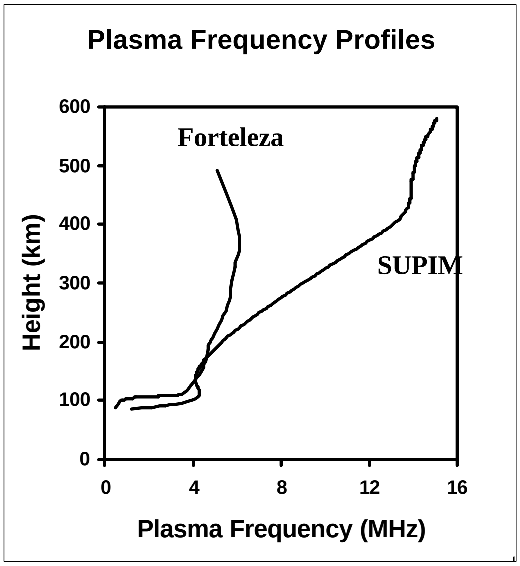

Figure 2: Vertical ionospheric profiles at 1130 UT. Forteleza profile obtained by inversion of corresponding ionogram in Figure 1. SUPIM profile adapted from Balan et al., 1997.

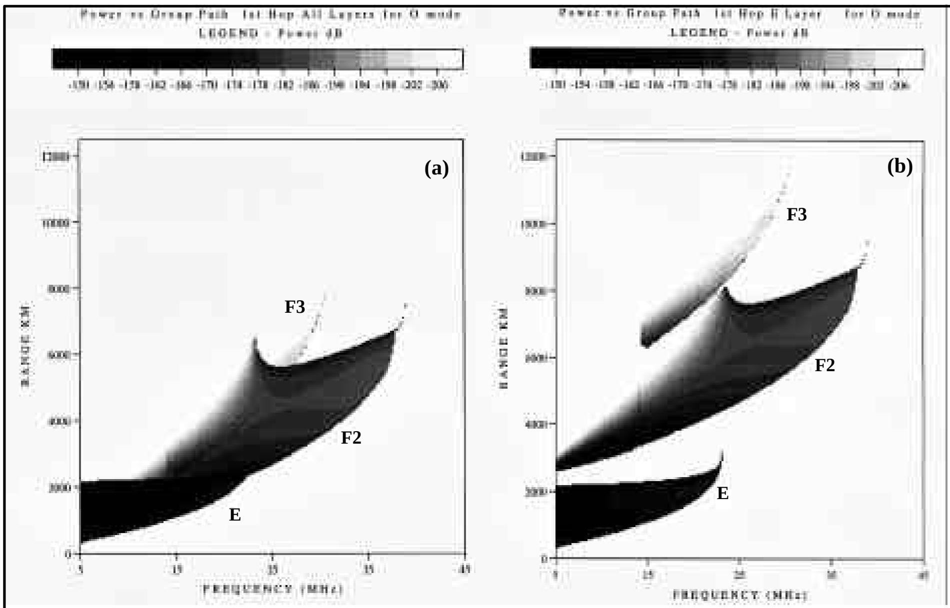

Figure 3. (a) Backscatter ionogram synthesized using SUPIM profile from Figure 2. (b) Layer traces displaced in group range.

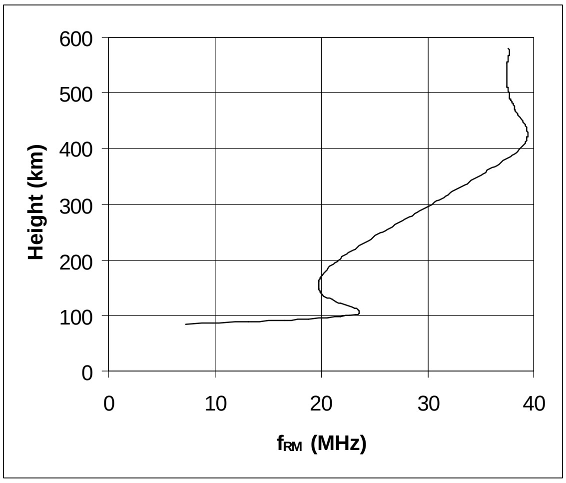

Figure 4. Maximum frequency that can be reflected by the plasma frequency at a particular height.

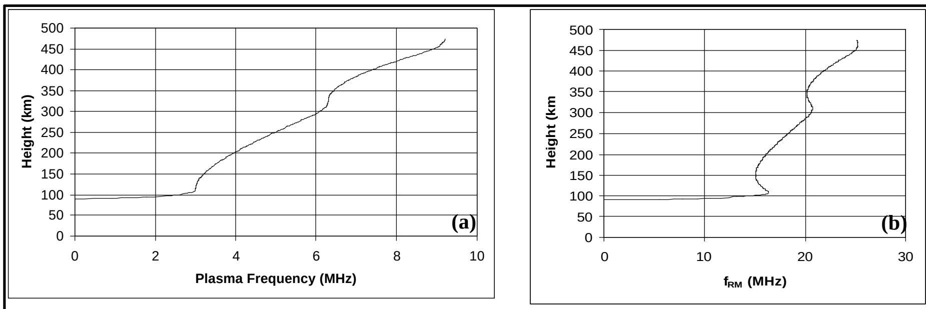

Figure 5. (a) Vertical ionospheric profile.
(b) Maximum frequency that can be reflected by the plasma frequency at a particular height

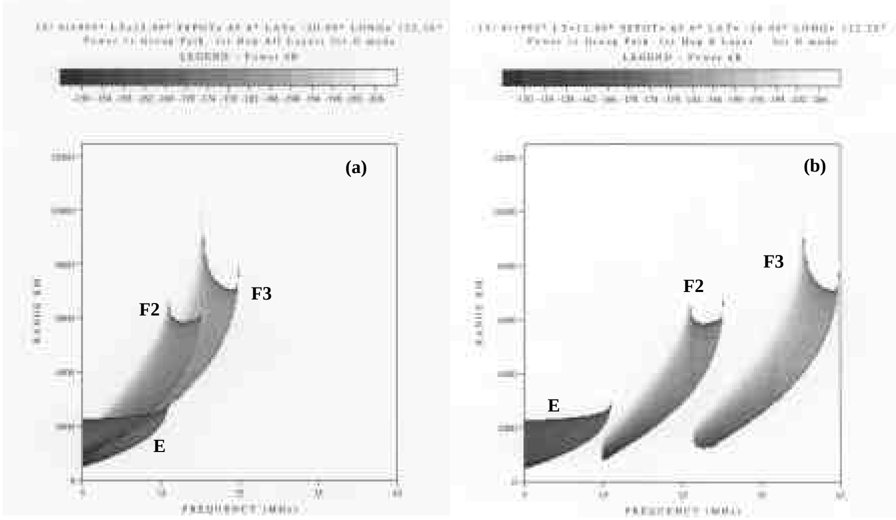

Figure 6. (a) Backscatter ionogram synthesizes using profile from Figure 5(a). (b) Layer traces displaced in frequency.

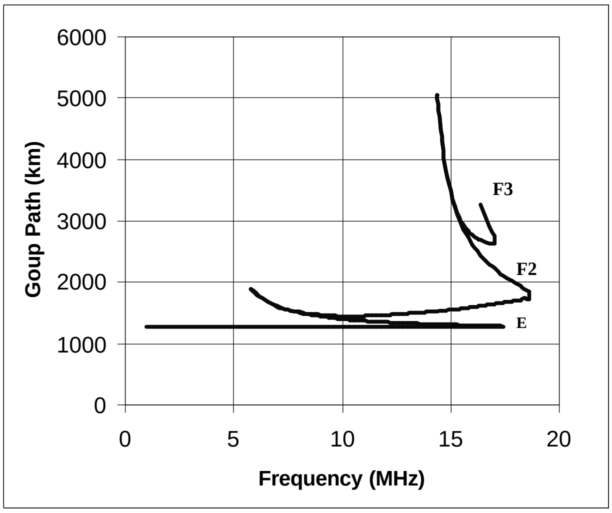

Figure 7. Oblique ionograms for SUPIM profile in Figure 2

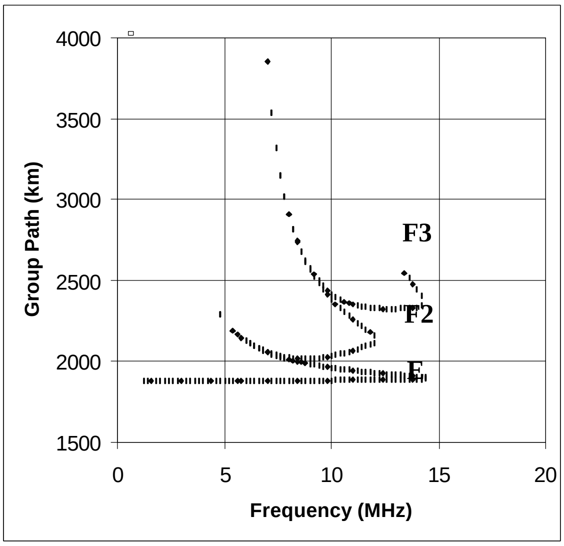

Figure 8. Oblique ionogram for ionospheric profile in Figure 5