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A Parametric Model of the Ionospheric Electron Density Profile for JORN

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ABSTRACT

To model the ionosphere, the Jindalee Operational Radar Network (JORN) uses a simple parametric description of the electron density profile at a large spatial grid of points. This technical note describes how to interpret those parameters to produce an electron density profile at any place and time by defining the ten parameters in use, and the rules used to construct six quasi-parabolic segments (QPS) that combine to produce a robust, complete, and flexible representation of the overhead electron density profile, eN(z). The basic model represents arbitrary shapes for three ionospheric layers (the E, F1 and F2 layers) and simple rules to characterise and quantify quasi-parabolic joining segments between each of the layers. These rules introduce the idea of the tenth ionospheric parameter F1q that controls the 'strength' of the F1 cusp between the F1 and F2 layers in addition to the three traditional ionospheric parameters (critical frequency, height of maximum electron density and semi-thickness of layer) describing each of the three layers. These extra joining segments are required to produce a continuous and smooth eN profile.

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Executive Summary

To model the ionosphere, the Jindalee Operational Radar Network (JORN) uses a simple parametric description of the overhead ionosphere's electron density profile at a large spatial grid of points. This note describes how to interpret those parameters in order to produce an electron density profile at any place and time. This report defines the ten parameters in use and explains the 6QPS profile rules used to provide a robust, complete and flexible representation of the overhead electron density profile. This is an inherent part of the JORN real-time ionospheric model (RTIM).

The basic model represents arbitrary quasi-parabolic shapes for three ionospheric layers (the E, F1 and F2 layers) and simple rules to characterise and quantify quasi-parabolic joining segments between each of the layers. These simple rules introduce the idea of the tenth ionospheric parameter F1q that controls the "strength" of the F1 cusp between the F1 and F2 traces, in addition to the three traditional ionospheric parameters (critical frequency, height of maximum electron density and semi-thickness of layer) describing each of the three layers. The extra joining segments are required to always produce a continuous and smooth electron density profile eN(z).

The report also shows how the simple model can be readily expanded to include the effects of multiple sporadic E layers in the ionosphere.

Numerous examples are presented to confirm that these 6QPS profile rules have the flexibility and robustness to represent vertical incidence sounder (VIS) traces accurately, both under a range of typical conditions and also during more exceptional ionospheric events, even with this limited number of free parameters.

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1. Introduction

The Jindalee Operational Radar Network (JORN) is an Australian Defence Force over-the-horizon radar (OTHR) network that uses high frequency (HF) radio waves refracted through the ionosphere to detect targets of interest at large ranges. The JORN generates a real time ionospheric model (RTIM) to model and correct for the complicated propagation path of the measured target detections.

To understand the behaviour of radio wave propagation though the ionosphere, JORN seeks to describe the ionosphere's electron density eN(x,y,z,t). To simplify the process of describing this multi-dimensional property this paper seeks to focus on the one-dimensional structure of the local vertical profile eN(z) at a fixed place and time. Typically this profile is understood to be made up of a smooth profile of electrons from three separate layers, the E layer, the F2 layer and between them a transitional layer called the F1. Additional layers sporadically but commonly present are called sporadic-E (Es) layers.

To further simplify the process of describing eN(z), the impact of Es layers is temporarily neglected (because they are exceptionally thin and sporadic), and the paper's focus is on describing the complex but smooth remaining profile with a limited number of parameters. Simple physics suggests that a single ionospheric layer in equilibrium would form the shape of a Chapman layer, [Davies, 1990]. While this is at best a simple approximation, it suggests that the key layer shape of eN(z) when it is dominated by a simple equilibrium will have a parabolic functional form near the layer peak. The challenge is to create an algorithmic model including three such layers simultaneously (representing E, F1 and F2 layers) and deciding how to "fill" the eN(z) profile in-between the layers. The goal is to produce a profile that is continuous and smooth and an accurate representation of reality.

2. Background

A three-parameter functional form called the quasi-parabolic (QP) layer has been used to describe the eN(z) profile shape of a single ionospheric layer [Croft & Hoogasian, 1968]. This description of a single ionospheric layer is adopted because it is approximately parabolic and produces both a flexible description of an ionospheric layer's shape eN(z) and because it enables an exact analytic estimation of the properties of HF radio wave paths that are propagating through it. This single layer QP profile is traditionally defined by three free parameters; a peak amplitude Nm, the height of that peak (maximum) hm, and a layer semi-thickness ym.

Further simple physics suggests that the dominant part of the relationship between the number density of the free electrons and the effective plasma frequency of radio waves propagating through it is also a simple quadratic i.e. $eN = C \times fp^2$ [Davies, 1990] where fp is the effective plasma frequency and the constant C is derived from the mass and charge of a free electron. The critical frequency fc is the layer amplitude in terms of frequency rather than number of electrons (Nm) and a plasma frequency profile fp(z) becomes equivalent to and synonymous with the electron density eN(z). An example of a single QP layer, scaled in terms of fp, and the associated HF virtual height of propagation, assuming a spherically symmetric ionosphere, is produced below in Figure 1.

This parameterised eN layer shape captures the basic properties observed in the corresponding HF propagation. The parameter describing the base of the layer,
hb = hm-ym controls the floor or starting point for the delay of ionospheric returns. The parameter describing the peak amplitude of the layer Nm, or equivalently the related critical frequency fc (where $Nm = C \times fc^2$), controls the peak frequency or asymptote at which propagation will penetrate the ionosphere and does not return to Earth. This results in the region of great propagation delay as the frequency at vertical incidence approaches fc. The parameter describing the layer semi-thickness ym controls the slope of eN(z) at any height and hence the rate of transition between these two limits; i.e. affecting the shape of the HF virtual height trace.

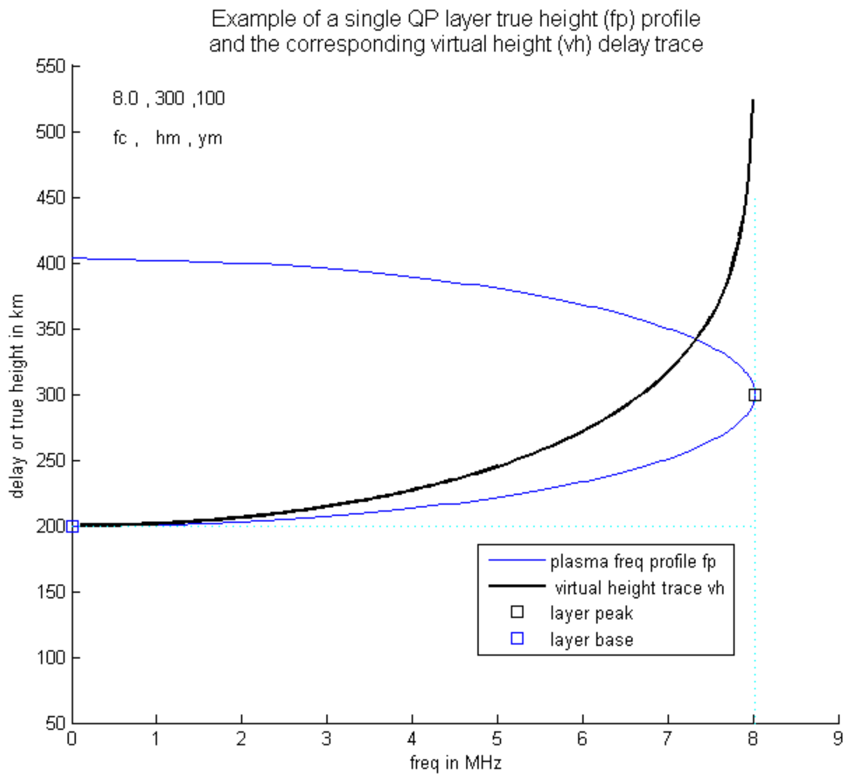

Figure 1 An example of a single-layer eN (fp) profile and the associated virtual height trace representing the synthesised vertical HF propagation delay.

Rather than describe an eN(z) or fp(z) profile by independently defining an eN value at a large number of levels (i.e. a fixed set of heights) several authors have generalised this simple parameterised model of a single eN layer to describe the ionosphere as a limited number of semi-independent layers. To represent a more complete eN(z) profile shape, encapsulating many layers and potential ledges, these authors created an algorithm to manufacture a set of adjacent QP segments that in combination define a complete eN profile [Dyson & Bennett, 1988]. This multiple QP segment (mQPS) description of eN(z) is constructed with a (potentially variable) number of adjacent segments, each valid over a small range of z, and each with changing curvature that joins together to produce a smooth and continuous profile. The generalised mQPS model can be arbitrary in its shape and number of parameters. However, a completely arbitrary shape is difficult to specify if the observations used to estimate the profile are incomplete. Such a continuous mQPS model of electron density and analytic raytracing theory of HF radio propagation can be used to synthesise (or invert) the properties of either vertical or oblique propagation [Chen, Bennett & Dyson, 1992 or Huang, Reinisch & Kuklinski, 1996].

Practical applications do not generally allow a profile with arbitrary resolution (either in levels or layers) to be defined because observations with arbitrary resolution are seldom available. A practical compromise is to depend on a limited and fixed set of QP segments jointly representing the E, F1 and F2 ionospheric layers. Simple layer models have previously been proposed and described by Dyson & Bennett [1992] and modified by Sun et al [2016] where the E, F1 and F2 layers with positive curvature are each joined with adjacent reverse curvature joining segments in a continuous and smooth way. Each of these models starts with a finite set of parameters describing the dominant 2 or 3 ionospheric layers and adds a limited set of rules or additional parameters that define the intervening transition or joining segments. The joining segments can be used to represent valleys of electron density between the two bounding layers, or they can be restricted to be monotonically increasing joins.

The challenge for any of these algorithms is to support a flexible parameterised set of profile shapes that produces a diversity of observed propagation trace features, and to do it under a wide range of ionospheric conditions. Of particular difficulty is the accurate representation of the variable strength of the F1 cusp (or point of maximum curvature) observed in HF virtual height traces. This varies from periods in the middle of some days when the F1 cusp is strong and distinct (and the position of the F1 critical frequency is clear) to periods when the transition between the F1 and F2 regions is much less distinct and the F1 L-condition is present [Baker, 1990]. At night, the role of the F1 layer is generally almost negligible and the parameters are only used to represent residual electrons under the F2 layer. Modelling these transitions has been addressed by several authors including Baker [1990], Baker & Burden [1992] and Baltazart & Wilkinson [1995].

One important point is that when the F1 cusp is not distinct, the frequency at which the F1 cusp is observed within the virtual height trace (i.e. fbF1 the frequency where the electron density profile gradient has a minima and the trace has maximum curvature) is not necessarily the same frequency as the parameter used to describe the peak of the underlying F1 layer (fcF1). This is because the F1 to F2 profile transition and join has potentially started below the peak of the F1 layer [Beynon & Thomas, 1956].

In contrast to this segmented approach, other functional approaches have adopted descriptions that build profiles from a sum of Epstein or Chapman layers that continuously exist everywhere [Radicella and Zhang, 1995]. These strongly couple together the parameters describing each layer in the final profile. Alternatively, instead of a smooth approach to profile modelling, the International Reference Ionosphere (IRI) has adopted an F1-F2 profile transition that is not inherently smooth [Reinisch and Huang, 2000] but has the F1 to F2 transition starting and ending at a single point on the F2 profile (with a discontinuity in the profile gradient). This allows a representation of a weaker F1 cusp by changing the whole interpretation of the overlap between the F1 and F2 layers. This is a different profile modelling approach to the mQPS approach adopted here and requires no additional parameters to describe the F1-F2 transition. It does, however, require a different interpretation of the parameters used to describe the F1 layer and results in a non-smooth eN profile. Other models adopt different profile rules regarding the interpretation of the ionospheric parameters and some of these are summarised in the AFRL Handbook of Geophysics and the Space Environment [1985].

Unlike a continuous model of eN(z) at a large number of levels, any layer or segment based algorithm will also require additional parameters to define the depth of the valley between the E and F1/F2 layers within the profile. One way to do this is discussed below.

3. The JORN 6QPS Parametric Model of the eN(z) Profile

The representation of the eN(z) or fp(z) profile starts with a set of 9 parameters

$$P9 = \{foE, hmE, ymE, foF1, hmF1, ymF1, foF2, hmF2, ymF2\} \quad (1)$$

to describe each of the E, F1 and F2 QP layers independently.

3.1 Main parameter constraints

One of the requirements of a useful parameterisation is to always be able to generate a valid profile from an arbitrary set of parameters. A valid profile is one for which the layers are logically ordered, in both critical frequency and height, and sufficiently separated so as not to engulf each other. This requirement is enforced in the algorithms in part by imposing a set of constraints on these P9 parameters before calculating eN(z) such that

$$foE\_min < foE < foF2 < foF2\_max \quad (2a)$$

$$foE\_min < foF1 < foF2 \quad (2b)$$

$$hmE\_min < hmE < hmF1 < hmF2 < hmF2\_max \quad (2c)$$

and

$$ymE > ymE\_min \quad (3a)$$

$$ymF1 > ymF1\_min \quad (3b)$$

$$ymF2 > ymF2\_min \quad (3c)$$

where the configuration parameters (e.g. foE_min, foF2_max, hmE_min and hmF2_max) are predefined to stop the algorithms selecting aphysical profiles (see Appendix A for the selected values)

These constraints represent a small limitation on the physical shape of the final profile but they impose some simple and reasonable limits on parameters such that the E layer is always lower than the F1 layer, which is itself always lower than the F2 layer.

Despite these preliminary constraints there is still a potential for such a three layer eN profile to provide an invalid set of adjacent segments if a layer entirely engulfs (or excessively overlaps) a neighbouring layer. An example of this is presented in Figure 2. To prevent this excessive overlap, additional constraints must be imposed on the eN parameters so that excessive overlap is not possible. These constraints are

$$hmF2-hmF1 > ymF2\_min \quad (4a)$$

$$hmF1-hmE > ymF1\_min \quad (4b)$$

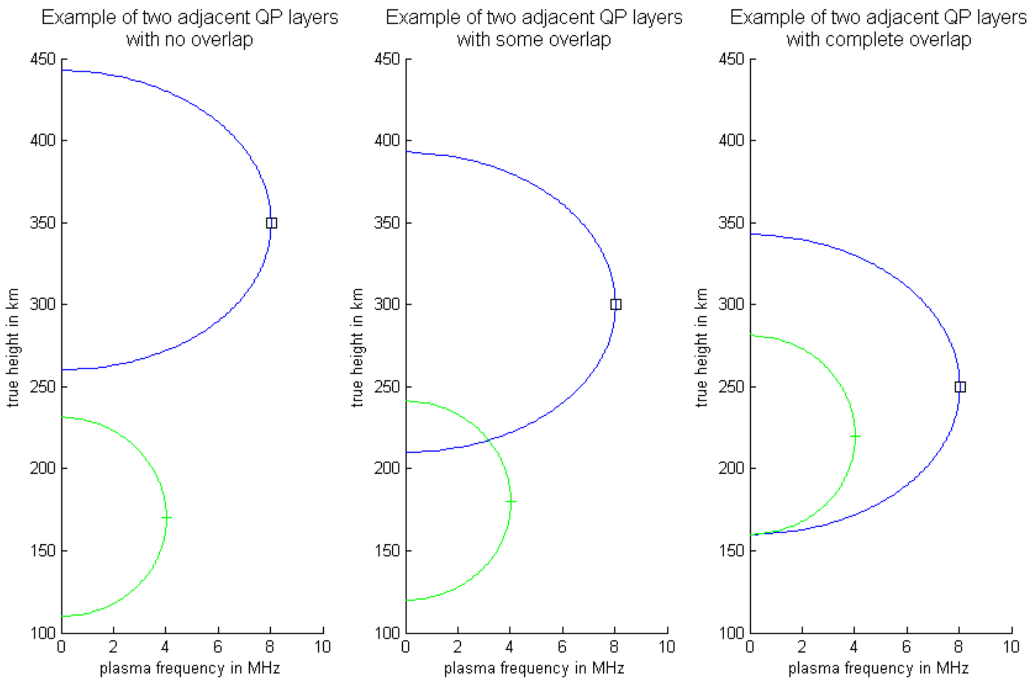

Figure 2 A pair of adjacent QP layers (a) with no overlap, (b) with partial overlap, and (c) with one layer completely engulfing another.

In combination, these constraints (equations 2-4) do not have a particularly large effect on the shapes of physically reasonable eN profiles that can be represented. However, one significant additional profile assumption has been made to significantly simplify the final eN profile, that is, it has been assumed that

Model decision 1:

$$foE < foF1 \tag{5a}$$

or in combination with equations (2a) and (2b)

$$foE < foF1 < foF2 \tag{5b}$$

This constraint is convenient but does impose a physical constraint on the profile, particularly at night, i.e. the peaks of the successive layers are monotonically increasing. This does not mean there can be no valleys but it changes the nature of any eN valleys between the E and the F region.

As an aside, it is worthwhile to note that the above equations contain inequalities, and to be guaranteed to produce smooth profiles, the algorithm needs to maintain those inequalities. To achieve this inequality, where appropriate, small gaps are introduced; i.e.

$$foF1 = \max(foF1, foE + \Delta fgapF1) \tag{6a}$$

where $\Delta fgapF1 = 0.01$ MHz and analogously

$$foF2 = \max(foF2, foF1 + \Delta fgapF2) \qquad (6b)$$

where $\Delta fgapF2 = 0.3$ MHz

3.2 Enforcing constraints

Most of the parameter constraints in equations 2-6 are simply enforced by testing the input set of parameters and adjusting the output parameters to satisfy the constraints; for example

$$ymE_{out} = \max(ymE_{in}, ymE_{min})$$

Some of the constraints above in equations 2-6 are interconnected and can be enforced in different ways or in a different order, potentially affecting the results. In order to a make any parameter modification minimal and consistent, our algorithms enforce these constraints in a fixed order, starting from the lowest layer and working up to the highest layer.

3.3 Calculating joining segments

The above parameterisation and constraints always produce a valid eN profile. Moreover, small changes in parameters will always produce small (or zero) changes in the derived HF propagation delays (except near a few critical points in the profile, where the propagation is highly sensitive to the profile shape). However, these profile rules are lacking two desirable properties:

1. The profile formed from the disjoint layers is continuous, but not smooth in its first derivative. Smoothness is desirable if we later wish to use this eN profile with numerical ray-tracing to model the HF propagation.
2. The relationship between the eN profile parameters and the corresponding observed HF propagation properties (such as virtual height) is not unambiguously invertible until we specify the eN content between each of the profile main layers in a physically meaningful and consistently smooth way.

To establish these two properties within our profile building algorithms, QP joining segments between each of the main layers are added such that these joining segments are continuous and smooth at both the upper and lower joining points. Dyson & Bennett [1988] and others have demonstrated the mathematics showing that given the parameters that define two adjacent positive QP segments one can always find the parameters that define an intervening joining segment that is a smooth and continuous join between the layers (starting at point [fk, rk] on the lower layer and going to intersection point [fj, rj] on the upper layer). Variable r is used to denote a radial distance from the centre of the Earth. Variable h is used to denote the corresponding height above the surface of the earth, such that h=r-RE. Variable z is a general descriptive height variable, where its exact interpretation as either r or h depends on the circumstances.

In the general case, there is a family of joining segments possible between any two QP layers; the exact segment properties depend on the intersection point selected. Figure 3 below shows a family of three possible joining segments that can be produced for one particular set of layer parameters, but three different joins. These joins are constructed to satisfy the constraint that the join within the eN profile is smooth and continuous.

The second major profile modelling decision made within the algorithm is intended to simplify our eN(z) profile and guarantee invertibility of the relationship between a vertical height trace and the corresponding eN profile. This is achieved by fixing the rules governing the E-F1 joining segment. This is done by adopting and enforcing a monotonically increasing eN profile. Components of this modelling decision, when applied to the join between the E and F1 layers, include:

Model decision 2: Apply an additional constraint to the F1 thickness so that the F1 layer does not overlap the peak of the E layer.

Model decision 3: Select the join from the E to the F1 layer that starts at the peak of the E layer (i.e., the solid line in Figure 3).

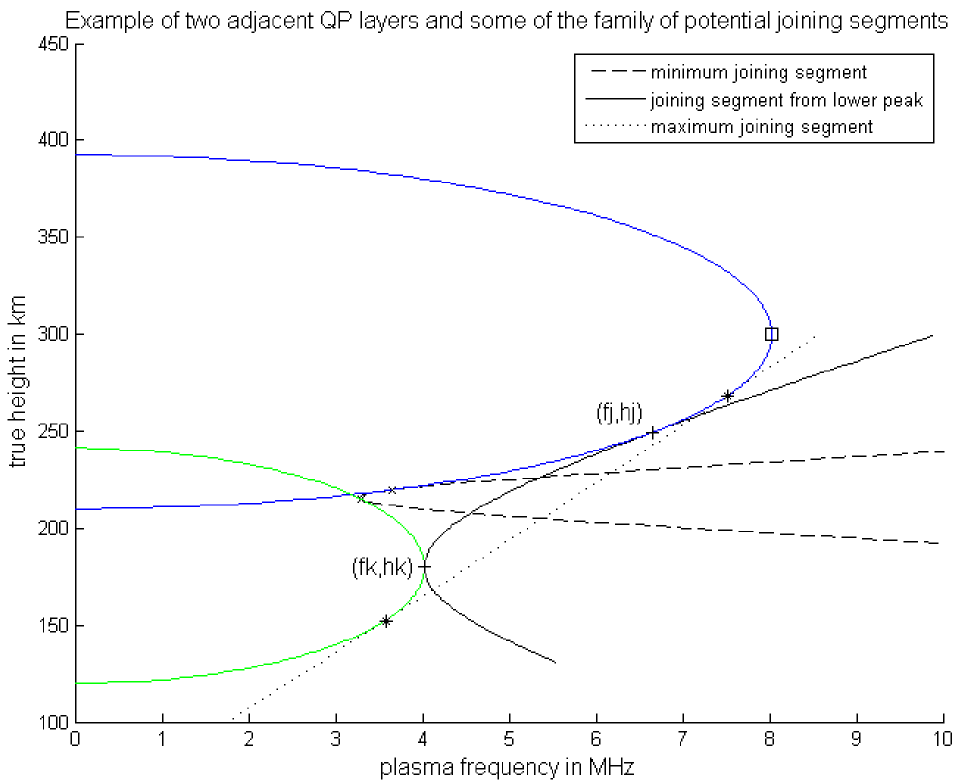

Figure 3 A picture of a part of the family of possible joining segments and the nomenclature used. Here (fk,hk) is the plasma frequency and height of the bottom of the joining segment while (fj,hj) is the plasma frequency and height of the top of the joining segment. The solid line is a special case when the starting point of the join is the peak of the lower layer.

An example of the typical E-F1 joined profile is presented in Figure 4 below. While this monotonically increasing eN(z) profile does not have the regularly observed E valley, the impact on the accuracy of the fitted trace in the F1 region is considered to be less important than the advantage of not having to set and estimate a new free parameter that controls the depth of the E-F1 valley.

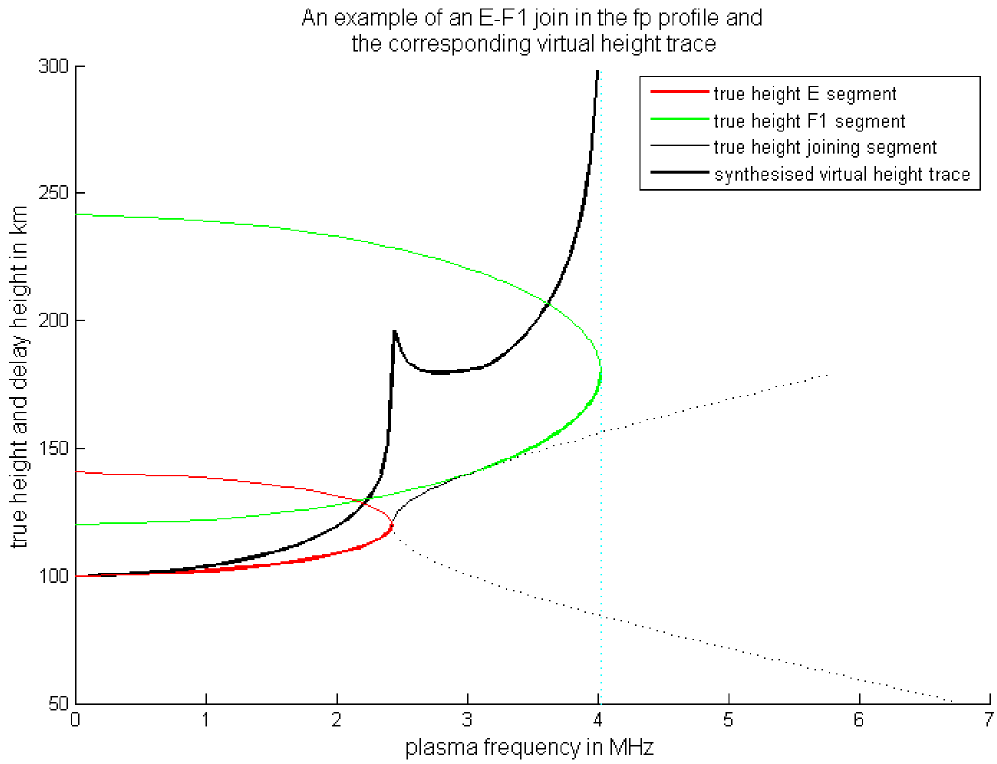

Figure 4 A picture of the eN profile with two layers (E and F1 only) and a simple standard E-F1 join, along with the corresponding virtual height trace.

Applying this same modelling decision to the joining segment between the F1 and F2 layers has been found to be problematic, because the observed trace cusp between the two traces would be forced to always be substantial. Observations suggest that there are regular times when the transition between the E and F2 traces is made up of a weak F1 cusp (sometimes referred to as the L condition), and hence, the algorithm adopts a parameterised profile description that admits this possibility. The additional modelling decision made in the JORN 6QPS algorithms is, therefore, to allow the parameterised F2 layer to (potentially) partially overlap the peak of the F1 layer, and allow the F1 to F2 joining segment to take on a range of possible values, from strongly overlapping to starting at the peak of the F1 layer.

Components of this modelling decision, when applied to the join between the F1 and F2 layers, include:

Model decision 4: An additional constraint to the F2 thickness (or F1 height), so that the F2 layer does not overlap all of the F1 layer (i.e. the F1-F2 join intersection radius from above on the F1 layer, rk_F1,is greater than the E-F1 join intersection radius on the F1 layer from below rj_F1).

Model decision 5: We select the join from the F1 to the F2 layer by assigning an additional parameter F1q that will define the start and end points within the set of possible joins.

An example of the typical range of profiles is presented in Figure 5 below. In this profile the additional F1q parameter represents a single dimensionless value in the interval 0 to 1 that defines the starting point of the F1-F2 join with respect to the range of admissible curves. F1q →= 1 represents a join at the peak of the F1 layer (and a strong F1 cusp) while F1q →= 0 represents a highly overlapped pair of layers and a weaker F1 cusp.

Mathematically a very large join when F1q =→ 0 can still be a valid solution, but an unreasonable profile (and an unlikely best fit to real data).

This set of constraints and joining segment rules results in a smooth three layer JORN QPS eN(z) profile, given a set of parameters

$$P10 = \{foE, hmE, ymE, foF1, hmF1, ymF1, foF2, hmF2, ymF2, F1q\} \quad (7)$$

and the application of the constraints discussed above, so that the parameters are valid.

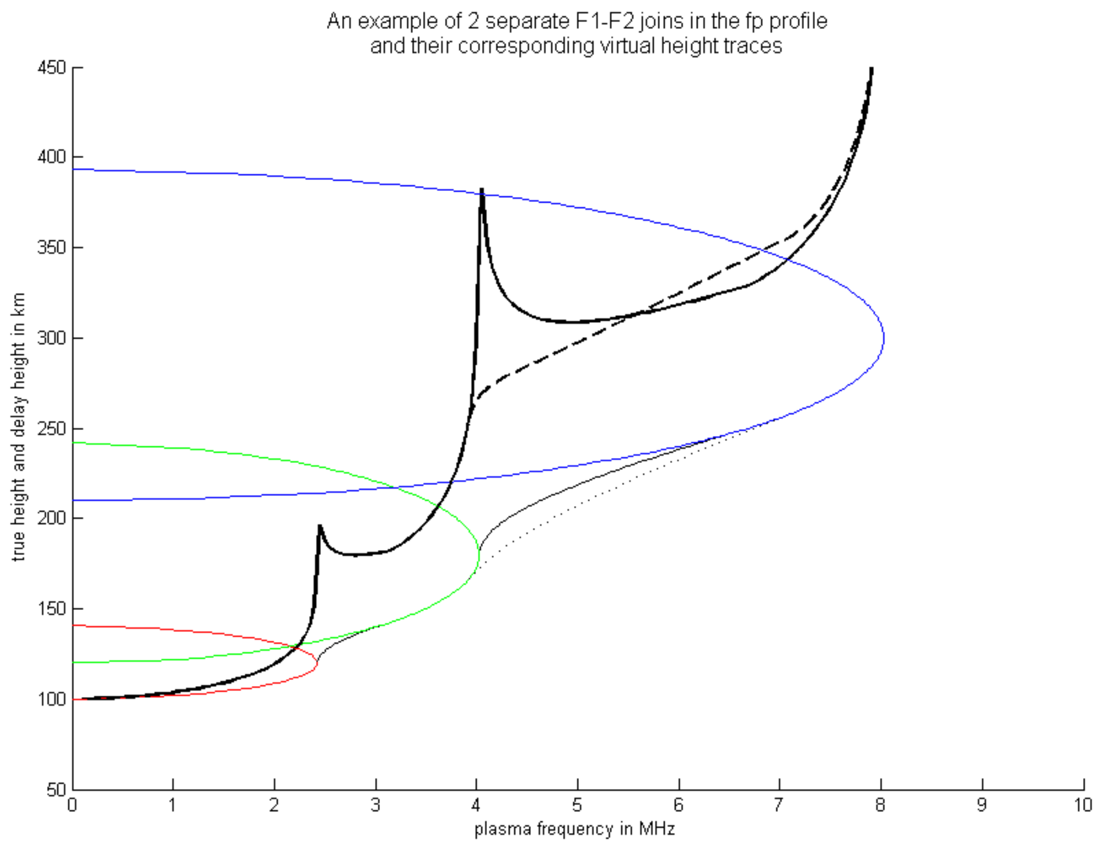

Figure 5 Two eN profiles with different F1-F2 joins and the corresponding virtual height traces.

3.4 Additional constraints, joins and parameter adjustments

Before leaving the algorithm definition, in order to examine the algorithm performance, it is worthwhile for completeness to note some additional details.

3.4.1 A sub-E joining segment

One of the requirements of this profile description, in order to support numerical propagation modelling, is that the final profile be continuous and smooth. While this is achieved between layers in the above algorithm, smoothness is not automatic at the base of the E layer, where the ionosphere transitions to the zero with a jump in the eN gradient. To fix this anomaly an additional new joining segment below the E layer is introduced (even when it is a residual E layer at night). To guarantee this layer has a small impact on the total profile this join is designed to be small, i.e. we start the join at hmsubE = hbE-Δh_{gap} where Δh_{gap} is commonly set to be 0.2*ymE.

This makes the total JORN eN(z) profile contain 6 QP segments described and named in Table 1 below.

Table 1 A table of QP segment names and numbers

1	2	3	4	5	6
subE	E	E-F1 join	F1	F1-F2 join	F2

Occasionally some of these segments will be very small in their extent or amplitude. However, the intent of the JORN profile algorithm is that, for any set of parameters P10, the algorithm will apply the parameter constraints necessary to assure a valid profile, and calculate a complete set of variables defining the amplitudes and heights of each layer and join. Using this algorithm, a complete, continuous and smooth eN(z) profile can always be constructed.

3.4.2 An fj max constraint and hmF1 adjustment

One additional practical constraint is applied routinely to stop the profile building algorithm from manufacturing an unrealistically large join between the F1 and F2 layers, particularly at night. At night, the role of the F1 layer is generally to represent the underlying residual electrons between the night-time residual E and the start of the F2 region. This is generally enforced for night-time profiles, by the exclusive use of a climatological model for foF1 rather than a fitted foF1, combined with the application of Δf_{gapF1} in the profile building rules:

$$foF1 = foF1\_model = foE\_model + \Delta f_{gapF1}$$

However, there is nothing to stop the base of the night-time F2 layer (hbF2) occurring far above the estimated night-time climatological hmF1. If this occurs, then our previous algorithm choices can result in a very large F1-F2 join and an aphysical trace appearance. The solution adopted is:

Model decision 6: Do not let the F1-F2 join frequency on the F2 layer (fj_F2) excessively close to the F2 peak i.e. $fj\_F2max = foF1 + \alpha \times (foF2 - foF1)$ where $\alpha = 0.75$.

To always be able to achieve this, there is a need to sometimes limit the range of allowed F1q values and/or, at night, change the height of the residual F1 (hmF1) such that a valid F1-F2 join is achievable. In general, the shape of the F2 trace can be strongly influenced by the height of the underlying residual E and F1. This α constraint limits the potential for unrealistic profile shapes but nothing helps like adjusting layer parameters (e.g. hmF1) to make a better fit. An example of a simple case of night-time hmF1 adjustment is presented below in Figure 6.

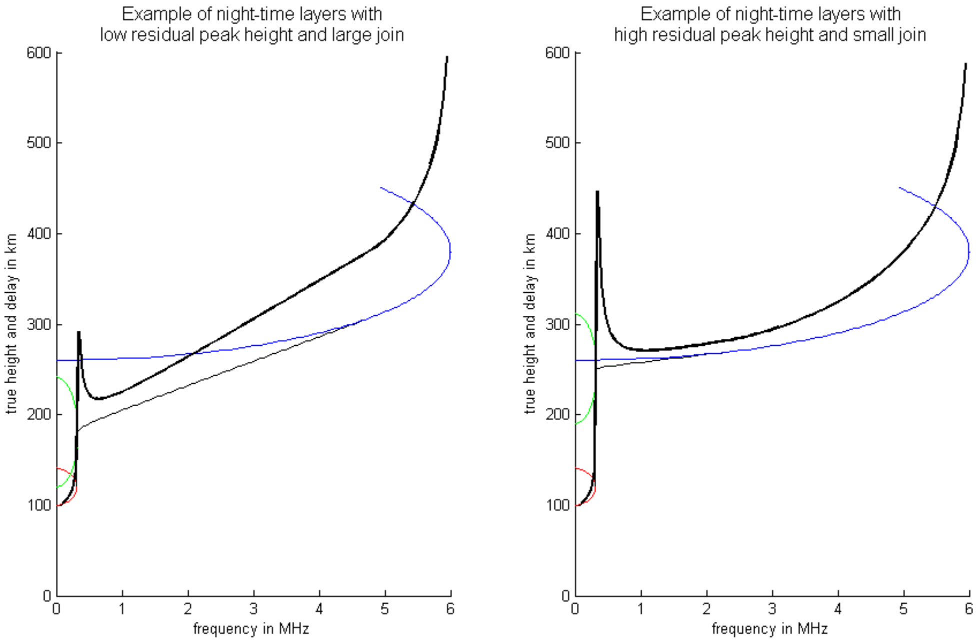

Figure 6 Two eN profiles and associated virtual height traces produced with different F1-F2 joins at night, before and after hmF1 alone is changed (pushed higher in the plot on the right).

4. The Typical Performance of the JORN 6QPS Profile Model

The preceding discussion demonstrates how to always enforce the construction of a valid, continuous and smooth profile. However, there is also a requirement to produce a flexible profile shape that accurately represents the observed data and the underlying true eN profile. With this in mind, this section attempts to demonstrate (with a small number of examples) that much of the variability observed in mid-latitude VIS traces can be accurately fitted and reproduced using this profile model driven with just ten degrees of freedom. A discussion of the fitting algorithm is left to another document.

Some examples of real and reconstructed virtual height traces are produced below in Figure 7. During the day, the E and F1 regions are present, and this is visible in the top row of Figure 7. These panels show the independent representations of the virtual height and shape of the E and F2 layers, as well as the transition between them within the F1 region over time.

In the top-left panel the day-time F1 trace cusp is clear but weak in the raw delay observations (black markers). The result is a large join in the true height profile (magenta line), enabling this weak F1 cusp to be simulated in the corresponding fitted trace (blue line). Later in the same day (the top-right panel), the F1 cusp is much stronger and the profile parameterisation has adjusted to represent this feature.

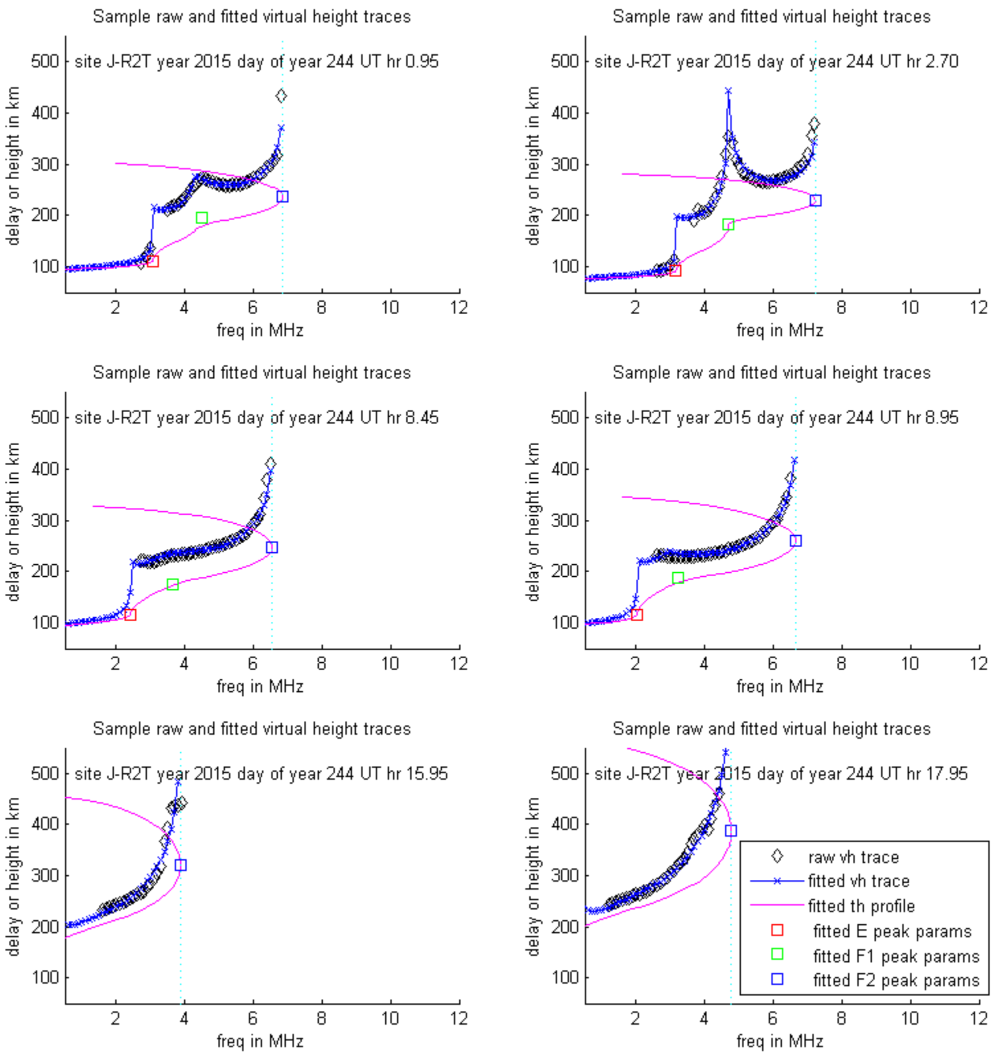

Figure 7 A series of raw traces (derived from ionograms), along with fitted traces and their corresponding true height profiles, from a single VIS site and a single day. Examples are drawn from day-time (top row), the day-night transition (middle row) and night-time (bottom row) periods.

In Figure 7, the middle row of two panels shows typical traces from the end of the day (8-9 UT), as the F1 and F2 layers transitions into night time conditions. This is demonstrated to occur in a smooth fashion as the estimated foF1 diminishes. The bottom row of Figure 7 shows two examples of night-time conditions, when the underlying E and F1 ionisation has reduced to residual levels and the F2 trace dominates (with varying amplitude, peak height and thickness).

While there are many ways to describe the accuracy of the reconstructed trace, the measure adopted in this algorithm chooses a representative frequency-to-delay ratio (1 MHz to 50 km), and uses this to define a normalised Euclidian distance between points on the original observed trace and the fitted trace, reconstructed from the parameterised profile. The normalised discrepancy for entire regions of the fitted trace can then be estimated as a weighted root-mean-square (rms) error which in the F2 region is typically small; for example 5 km of difference when the trace slope is horizontal gives the same contribution as 100 kHz of difference when the trace slope is vertical.

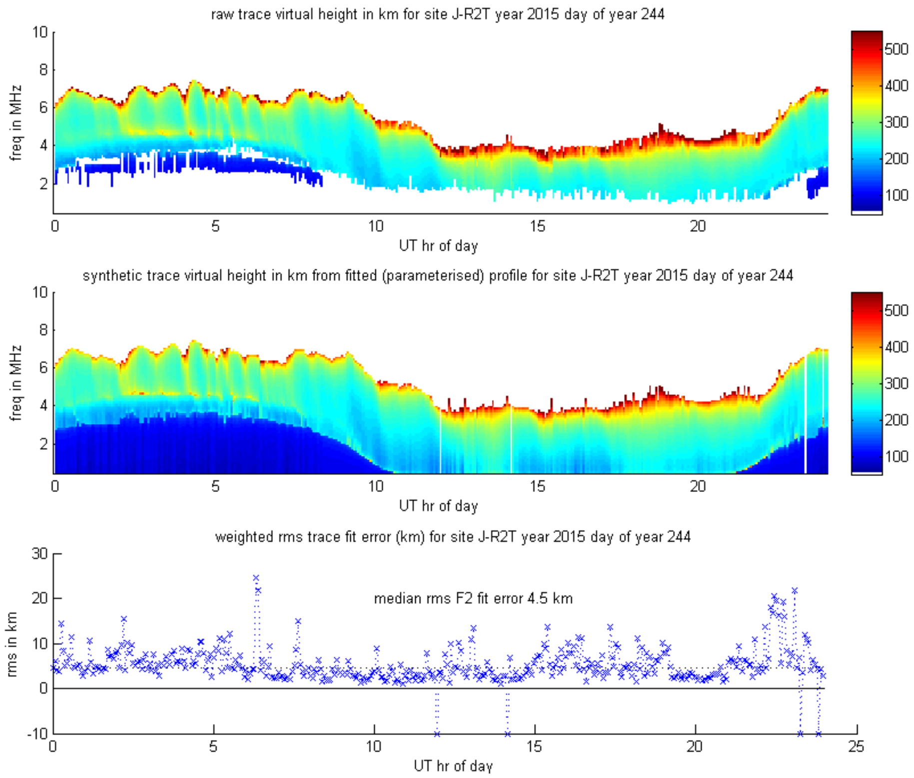

Figure 8 An image of the raw and fitted virtual height traces, and the corresponding error between them for a single VIS site and a single day from 2015.

Figure 8 shows a full UT day of 384 time samples (one every 3.75 minutes) comparing raw (observed) versus synthetic (fitted) traces. This case is representative of a wide range of days and sites. For this site and day, the median rms F2 fit error is found to be <5 km and the failure rate of fits is <2%. A failure is declared if no valid profile could be obtained or the rms error was > 25 km. The rms when a fit fails is arbitrarily set to -10, just to keep track of these cases.

Many features of ionospheric variability and the limitations of the vertical incidence soundings can be observed in Figure 8. However, the focus of this report is to demonstrate that the profile building routines are flexible enough in their shape characterisation to reliably and accurately represent the shape of the VIS observations.

5. Extensions

5.1 Extensions to include sporadic-E

While you can add Es layers with a true height (hEs) and amplitude (foEs) as additional QP segments with very narrow ymEs [Norman et al., 2001] this is potentially more complexity than is needed. A simpler solution is to add the Es layers as a conceptual mirror model at the height of hEs, embedded within the complete eN profile and use this mirror model as the propagation model to represent the Es traces observed in the soundings. For a given Es mirror height, the excess delay versus frequency from propagation through the underlying E region can be approximated [Beynon and Thomas, 1956] and added to the delay associated with a simple mirror reflection. Hence, the HF propagation properties resulting from the inclusion of an Es layer can be represented without explicitly adding extra terms into the eN(z) profile description. This is what has been adopted.

5.2 Extensions to include an E-F1 valley

While the above algorithm, for the sake of simplicity, has adopted a monotonic eN(z) profile, it is a reasonably simple generalisation to allow eN(z) valleys to be present if you introduce an additional parameter to define the depth of any valley. Valleys between the E and F regions are often described in the literature [Titheridge, 2013; Sun, 2016]. One easy way to achieve this is to define the depth of the valley as a fixed number or a fixed fraction of the maximum amplitude of the E and F1 layers. Using a fixed maximum depth e.g. vD = 200 kHz and allowing model foF1 to be less than foE at night (where foF1 >= foE-vD) introduces the presence of valleys without adding additional parameters that need to be fitted. If you have an instrument that admits the possibility of fitting an uncertain depth to the E-F1 valley then that too could be fitted.

An example of this extended profile with a valley depth fixed at 200 kHz and the night time residual foE at 0.33 MHz, is presented below in Figure 9. Note that at this stage we have not adopted valleys in the JORN usage, but either a fixed or a variable valley depth is possible if there are data available to make a determination of the valley depth.

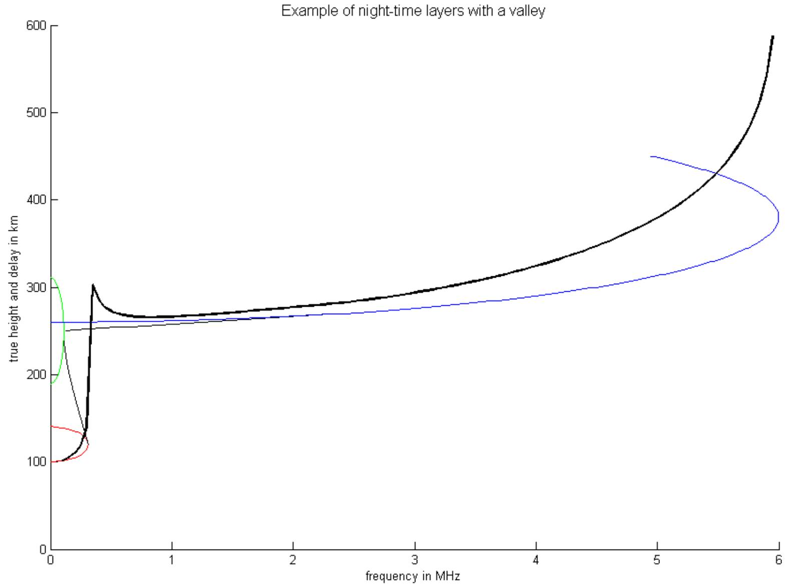

Figure 9 An fp(z) profile with a shallow fixed E-F1 valley and the corresponding virtual height trace (thick black). The fp(z) components are E (red), F1 (green) and F2 (blue),along with their joining segments (thin black).

5.3 Extensions to include variations in the topside

The above algorithm has a single semi-thickness parameter ymF2 for the F2 layer. For simplicity, this single parameter is used for both the bottom and the top half of the F2 layer (because we are mainly interested in bottom side profiles in the JORN usage). The top of the F2 ionisation above the peak of the F2 layer can be used to approximate the ionospheric component of the total electron content (iTEC). Regrettably, this QP model shape and ymF2 value is clearly going to neglect a great part of the top-side contribution to the iTEC. To correct for this deficiency additional QP segments can be added above the standard JORN 6QPS profile, or the top-side F2 segment can be assigned a different scale height (semi-thickness) to the bottom-side (i.e. ymT ≠ ymF2). Discussion concerning how to select and assign ymT as an additional variable contributing to the eN profile description is left for another time, but with a simple extension, this set of profile routines can be used for that purpose.

6. Conclusions

The ten-parameter 6QPS profile rules described provide a robust, complete and flexible representation of the overhead electron density profile particularly when expanded to include additional parameters to represent sporadic E. The basic model represents arbitrary shapes for three ionospheric layers (the E, F1 and F2 layers), and simple rules to characterise and quantify quasi-parabolic joining segments between each of the main layers. These simple rules introduce the idea of the tenth ionospheric parameter F1q that controls the "strength" of the F1 cusp between the F1 and F2 traces, in addition to the traditional three ionospheric parameters describing each of the three main layers. The value of this F1q parameter can be determined (along with the other parameters) by fitting a synthetic virtual height trace to a real observed ionogram trace.

Examples presented confirm that these 6QPS profile rules have the flexibility and robustness to represent VIS traces accurately, both under a range of typical conditions and during more exceptional events even with this limited number of free parameters.

7. References

1. Davies, K. (1990) 'Ionospheric Radio'
2. Croft T.A. and Hoogasian H. (1968) 'Exact Ray calculations in a quasi-parabolic ionosphere with no –magnetic field', **3** 69-74 *Radio Science*
3. Dyson P.L., and Bennett J.A. (1988) 'A model of the vertical distribution of the electron concentration in the ionosphere and its application to oblique propagation studies' **50** 251-262 *Journal of Atmospheric and Terrestrial Physics*
4. Dyson P.L., and Bennett J.A. (1992) 'Exact ray path calculations using realistic ionospheres', **139** 407-413 *IEE Proceedings-H*
5. Sun J., Zhang X-J. , Wang S., Gong ZQ. and Fang G-Y. (2016) 'Multi-quasi-parabolic ionosphere model with EF-valley', **59** 1-7 *Annals of Geophysics*
6. Chen J., Bennett J.A. and Dyson P.L. (1992) 'Synthesis of oblique ionospgrams from vertical ionograms using quasi-parabolic segment models of the ionosphere', **54** 323-331 *Journal of Atmospheric and Terrestrial Physics*
7. Huang X., Reinisch B.W. and Kuklinski W. S. (1996) 'Mid-point electron density profiles from oblique ionograms', **39** 757-761 *Annali Di Geofisica*
8. Baker D.C. (1990) 'Extensions of the multi-parabolic ionosphere model to the F1-layer L condition', **26** 1301-1303 *Electronics Letters*
9. Baker D.C., and Burden J.J. (1992) 'Effect of F1-layer conditions on ranging accuracy for SSL HFDF systems' **28** 1956-1958 *Electronics Letters*
10. Baltazart V., and Wilkinson P. (1995) 'F1 layer modelling of ionospheric electron density distribution' **31** 1816-1817 *Electronics Letters*
11. Beynon W.J.G., and Thomas J.O. (1956) 'The calculation of the true heights of reflection of radio waves in the ionosphere', **9** 184-200 *Journal of Atmospheric and Terrestrial Physics*
12. Radicella S.M., and Zhang M-L. (1995) 'The improved DGR analytical model of electron density height profile and total electron content in the ionosphere', **38** 35-41 *Annali Di Geofisica*
13. Reinisch B.W., and Huang X.(2000) 'Redefining the IRI F1 layer profile', **25** 81-88 *Advances in Space Research*
14. Klobuchar, J.A., McNamara, L. F.et al (1985) 'AFRL Handbook of Geophysics and the Space Environment'
15. Norman R.J., Dyson P.L., and Bennett J.A. (2001) 'Modelling and mapping sporadic E using Backscatter Radar', ANARE Reports, 146, 147–164
16. Titheridge J.E. (2003) 'Model results for the daytime ionospheric E and valley regions', **65** 129-137 *Journal of Atmospheric and Solar Terrestrial Physics*

Appendix A Typical Profile Configuration Parameters

Table 2 Table of typical profile configuration parameters.

Parameter name	Value
foE_min	0.33 MHz
foF2_max	20.0 MHz
hmE_min	90 km
hmF2_max	600 km
ymE_min	5 km
ymF1_min	10 km
ymF2_min	20 km
Δf_{gapF1}	0.01 MHz
Δf_{gapF2}	0.3 MHz
Δh_{gap}	0.2*ymE
α	0.75

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19. ABSTRACT

To model the ionosphere, the Jindalee Operational Radar Network (JORN) uses a simple parametric description of the electron density profile at a large spatial grid of points. This technical note describes how to interpret those parameters to produce an electron density profile at any place and time by defining the ten parameters in use, and the rules used to construct six quasi-parabolic segments (QPS) that combine to produce a robust, complete, and flexible representation of the overhead electron density profile, eN(z). The basic model represents arbitrary shapes for three ionospheric layers (the E, F1 and F2 layers) and simple rules to characterise and quantify quasi-parabolic joining segments between each of the layers. These rules introduce the idea of the tenth ionospheric parameter F1q that controls the 'strength' of the F1 cusp between the F1 and F2 layers in addition to the three traditional ionospheric parameters (critical frequency, height of maximum electron density and semi-thickness of layer). These extra joining segments are required to produce a continuous and smooth eN profile.