



NeXtYZ: Three-dimensional electron density inversion for dynasonde ionograms

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[1] The problem of electron density inversion of digital ionograms is reconsidered from the viewpoints of new possibilities and of modern requirements. The data processing system of an advanced ionosonde (the dynasonde) provides accurate measurements not only of echo group range but also of direction of arrival, among other physical parameters, thus yielding the three-dimensional distribution of apparent echolocations in each ionogram recording. An iterative ray-tracing approach is described here to recover the parameters of a quite sophisticated three-dimensional (so-called wedge-stratified ionosphere) model of the local electron density distribution, characterizing its actual vertical $N_e(h)$ profile together with horizontal gradients and general tilts. The power of a contemporary PC is sufficient to accomplish this analysis quickly. This approach is implemented in the algorithm introduced here, is named “NeXtYZ,” and is pronounced “next wise.”

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1. Introduction

[2] The problem of real-height electron density inversion from ionosonde data has a long history, starting with *Appleton* [1930]. It has always been formulated essentially as an applied mathematical task and has therefore required a set of significant physical idealizations. A main simplification inherent to all “profile inversion” methods (until now) is the assumption of a horizontally plane-stratified ionosphere, thus reducing the problem to only one dimension. All plasma density surfaces are then horizontal planes, and only a vertical gradient is assumed. The wave vector of a sounding signal propagating in this medium is always vertical. Lower frequencies (and signals of both characteristic polarizations) pass through exactly the same plasma densities up to (and down from) their reflection heights. The radio propagation direction relative to the geomagnetic field, an important parameter of the inversion calculations, is simply assumed to be the local dip angle.

[3] The actual properties of the real ionosphere differ significantly from this idealistic picture. Practically all

processes in the ionosphere create horizontal gradients of electron density. Specific sources of large-scale horizontal gradients and tilts include the solar terminator (near sunrise and sunset), acoustic gravity waves and traveling ionospheric disturbances, storm time density enhancements, the equatorial anomaly, plasma bubbles, particle precipitation, and the general latitudinal/longitudinal dependence of the ionosphere. Midscale ($\sim 10\text{--}100$ km) and small-scale ($\sim 0.1\text{--}2$ km) irregularities add additional complexity to the ionosphere, leading to multi-beam reflections and “spreading” of echoes over large intervals of group range. In combination, these effects cause the sounding signal to propagate along non-canonical raypaths that only by chance are “vertical.” Thus actual data are usually in more or less explicit disagreement with the usual assumptions. Conventional inversion methods are consequently unreliable: They often cannot cope with internal contradictions of the input data and either fail numerically or produce distorted and always inaccurate results. Indeed, the inaccuracies are unknown and are nonquantifiable by these methods. Even relatively small tilts result in the use of an incorrect value for the propagation angle between the wave vector and magnetic field, with serious consequences for certain aspects of the inversion problem [*Wright*, 1990].

[4] Two methods of ionogram inversion widely used at present, POLAN [*Titheridge*, 1985] and NhPC (part of the Digisonde data processing system ARTIST)

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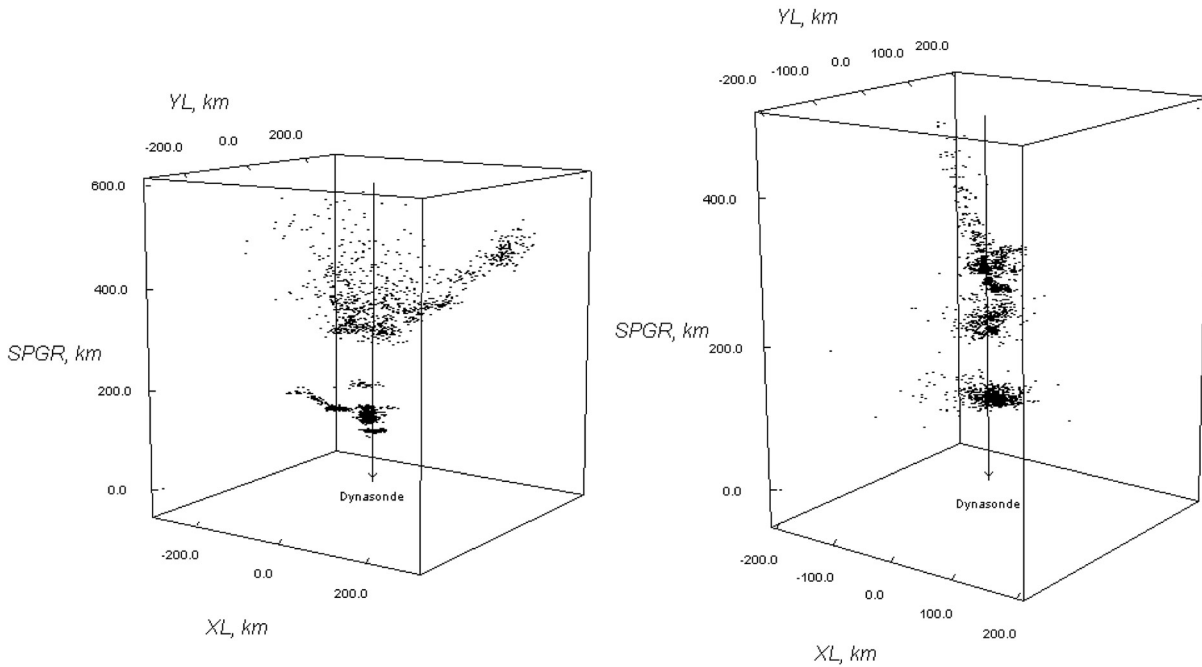


Figure 1. Examples of the three-dimensional distribution of apparent echolocations obtained by the automated data analysis procedure DSND for dynasonde measurements (left) at EISCAT Tromsø and (right) at Bear Lake Observatory, Utah.

[Reinisch and Huang, 1983], were developed more than 20 years ago, and little new attention has since been given to the problem. However, new opportunities arise from the computing power of modern PCs, and new requirements are now placed on the quality of ionospheric profile information. The latter include the need for realistic error assessments in modern assimilative modeling [Schunk *et al.*, 2004; Wang *et al.*, 2004; Khattatov *et al.*, 2004]. New opportunities and new requirements are weighty reasons for reconsidering the problem of electron density inversion from ionograms.

[5] Meanwhile, modern digital ionosondes (i.e., dynasondes) have advanced their capabilities to measure accurately both the group time of propagation and the directions of arrival for each ionogram echo. Three-dimensional distributions of apparent echolocations are presented in Figure 1.

[6] Each echolocation datum in these plots represents the end point of a “group path vector” [Paul *et al.*, 1974] aligned with the direction of arrival of the echo as measured at the dynasonde location, of length equivalent to half the group time of propagation, which is determined with remarkable precision by the stationary phase method. Actual positions of the reflection points (where the reflection conditions are met) are not measured directly and will differ because of refraction in the inhomogeneous magnetized ionospheric plasma. In the

“forward problem,” these effects can be calculated by ray tracing if the plasma distribution is known in three dimensions. In the inversion problem, ray tracing becomes a component in a procedure to reconcile the spatial electron density distribution with the measured echo ranges and their angular positions. This is the basic strategy of the new inversion scheme NeXtYZ.

[7] Three-dimensional (3-D) ionogram inversion does not aspire to the spatial coverage of radio tomography. The characteristic feature of the “all-sky view” of the ionosonde is its extraordinary sensitivity to local spatial structure, providing the perspective from a single ground location. The 3-D ionogram inversion problem may be formulated as the recovery of parameters of a parameterized model that describes locally both the vertical and horizontal gradients of ionospheric plasma density. The “wedge-stratified ionosphere” (WSI) model is the appropriate substitution for the former “plane-stratified ionosphere” model.

2. Wedge-Stratified Ionosphere

[8] In the WSI model, the plasma density surfaces are to be represented locally for small increments in plasma frequency f_p at a sequence of ranges h_i along the vertical axis, by slanted sections of “frame” planes; the slope of each frame plane is characterized by the two horizontal

components n_x , n_y , n_z of its normal vector. The normal to the plasma density surface determines the local direction of the total gradient in the layer.

[9] The WSI model makes reasonable assumptions about the distribution of plasma density between two frame planes inside a “wedge.” The basic requirement is, of course, that the plasma density is constant over each frame plane. Frame planes should not intersect within the ionosonde’s “field of view”: Since the WSI is a local model of the plasma density distribution, frame plane crossings are allowed outside their regions of relevance.

[10] There are some simple functional expressions that meet these requirements and that work well enough for inversion purposes: Plasma density depends only on the solid angle between adjacent frame planes. Alternatively, this dependence may use the variable $\rho = l/(l + d)$, varying from 0 to 1 between two planes, where l is the distance from a point to the lower frame plane and d is the distance to the upper frame plane. The dependence of the plasma density on ρ may be linear, or of higher order, to provide approximate continuity of the plasma density gradient at wedge boundaries within the ionosonde’s field of view.

[11] It is worth noticing that propagation of the sounding signals in the WSI model is essentially three dimensional. Analytic approximations of this process are not very helpful, so numerical ray-tracing methods are used instead.

[12] The principal feature of the WSI model is to describe the variation of local three-dimensional tilts of ionospheric layers with height. The option of a one-dimensional (i.e., vertical) profile is not lost: When the spatial distribution of the plasma density is available, any one-dimensional cross section may be retrieved without special difficulty.

[13] The NeXtYZ versions active at present produce parameters of a single family of WSI laminae for each ionogram. This approach is adequate for many purposes, and it has the potential to evolve to include a more elaborate description of complicated ionospheric situations. When an ionogram has several traces pertaining to a common frequency band but with distinctively different echolocations, each of the traces may be used to form a separate branch of the WSI model. This will lead in future work to the idea of a branching WSI model that allows a more complete characterization of observed ionospheric plasma structures.

3. Inversion General Principles

[14] Considering our introductory remarks about the influence of ionospheric irregularities on the parameters of sounding signals, there are certain requirements of a modern electron density inversion algorithm.

[15] 1. Statistical features and ambiguity in the data: The algorithm should easily accommodate data containing a significant random component or ambiguity caused by natural spatial variability in the ionospheric plasma density below a chosen level of detail.

[16] 2. Comprehensive input: The algorithm should use all of the available experimental information about the spatial properties of the electron density distribution; at present this information is expressed by group ranges and angles of arrival of radio echoes. Echoes are also, of course, discriminated according to their magnetoionic polarization.

[17] 3. Physically meaningful spatial resolution: Specific ionospheric conditions should dictate the shape of the electron density profile produced by the process; an approach based on fitting a preset combination of functions to the whole ionospheric profile is not acceptable.

[18] To meet these requirements, NeXtYZ implements the following principles and steps.

[19] 1. Most of the simplifying assumptions of contemporary inversion algorithms are replaced by numerical ray tracing for all legitimate ionogram echoes, taking into account their observed angles of arrival.

[20] 2. The inversion proceeds from bottom up, in a succession of thin plasma frequency layers (“wedges”). There are both minimum and optimum values preset for the plasma frequency step, but generally, it is controlled by the local echo density of particular ionogram traces contributing to the current plasma frequency interval: We need a sufficient number of echoes reflected within each wedge to solve the optimization problem described below. Through a convenience of preparatory dynasonde data processing, echoes have been organized into “traces,” and traces have been associated according to their polarizations [Wright and Pitteway, 1998]; traces of both polarizations, when available, contribute equally in NeXtYZ.

[21] 3. The inversion is done by solving a least squares optimization problem, minimizing the residuals between calculated and actual propagation times and directions for individual echoes.

[22] 4. To deal with the inescapable “starting problem” (practical observations are never obtained from the smallest ionization densities), the first step is solved simultaneously for parameters of the lowest plasma layer (wedge) and for three correction coefficients of a daytime D (or nighttime E) ionization model [Titheridge, 2000, 2001, 2003b]. This model is joined seamlessly to the first inversion starting interval.

[23] 5. All plasma wedges pertaining to observed monotonic parts of the ionospheric layer are treated using the same iterative procedure. Parameters of all underlying wedges remain unchanged. The vertical position h_{i+1} of the next frame plane (corresponding to plasma frequency $f_{p\ i+1}$) and its orientation (n_x , n_y , n_z) are determined as a result of a special optimization

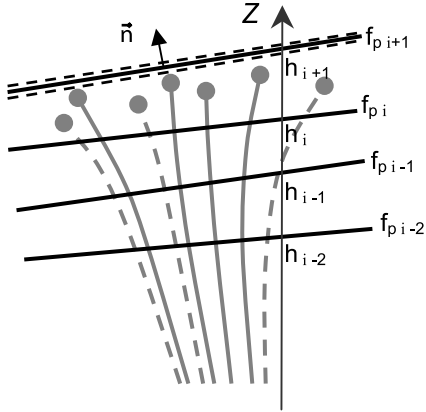


Figure 2. Geometry of the optimization problem. Each iteration of the optimization procedure requires calculation of the group propagation times for all echoes reflected within the current wedge. This calculation is done using numerical ray tracing, with the measured direction-of-arrival angles as initial conditions. Symbolic images of the raypaths (solid lines, ordinary polarization; dashed lines, extraordinary polarization) and of corresponding reflection points are shown in this sketch by gray lines in two-dimensional projection. Two already-determined underlying wedges and the current ($i+1$) topmost wedge boundary are shown.

procedure for residuals between measured and calculated parameters of those echoes that are reflected between $f_{p,i}$ and $f_{p,i+1}$ (see Figure 2).

[24] 6. When the observations give indications of an E - F valley, its general shape is determined from a recent model [Titheridge, 2003a]. Parameters of the valley model are then adjusted according to echoes pertaining to the F region in the same optimization procedure as is used to obtain characteristics of the next plasma wedge. As with all strata, echoes of both polarizations are treated equally; it is known that within “unseen” valley and starting intervals, the independence of the two polarizations contributes useful information to constrain the profiles.

[25] 7. In the vicinity of E , F layer peaks, the optimization problem is solved for the parameters of a Chapman layer model, instead of the vertical positions of individual frame planes. Orientations of frame planes are still determined in a special optimization procedure. This approach obtains an accurate fit for each layer peak and estimates of the parameters for a physics-based model of the topside ionosphere [Wright, 1960a, 1960b].

[26] 8. The well-known magnetoionic phenomenon of “lateral deviation” [Budden, 1985, p. 273] causes echoes of ordinary and extraordinary polarizations to sample different meridional regions of the ionosphere near their reflection levels. Meridional gradients have been a major cause of inconsistency and failure in past attempts to

combine both polarizations in ionogram inversion. In NeXtYZ, such inconsistencies are resolved properly to mean values of horizontal gradients.

[27] 9. Calculated positions of reflection points and times of propagation for each of the echoes that were used in the inversion are kept in the output arrays. When parameters of the WSI model are fully available, ray tracing is performed for those echoes that did not participate in the inversion procedure (traces of lateral reflection, sporadic layers), to provide calculated positions of their reflection points in the output also. This allows NeXtYZ to represent accurately in real three-dimensional space all significant ionospheric structures that produced echoes.

4. Numerical Ray Tracing

[28] The ray-tracing algorithm used by NeXtYZ is based at present on the method of characteristics [Kravtsov and Orlov, 1990] for the eikonal equation

$$H(\mathbf{k}, \mathbf{r}) = \frac{1}{2} [k^2 - n^2(\mathbf{p}, \mathbf{r})] = 0, \quad (1)$$

resulting in the following set of equations describing behavior of the ray, of the wave vector, and of the group range:

$$\begin{aligned} \frac{d\mathbf{r}}{d\tau} &= \frac{\partial H}{\partial \mathbf{p}} = \mathbf{p} - \frac{1}{2} \frac{\partial n^2}{\partial \mathbf{p}} \\ \frac{d\mathbf{p}}{d\tau} &= -\frac{\partial H}{\partial \mathbf{r}} = \frac{1}{2} \frac{\partial n^2}{\partial \mathbf{r}} \\ c \frac{dt}{d\tau} &= n^2 + \frac{1}{2} \cdot \omega \cdot \frac{\partial n^2}{\partial \omega}, \end{aligned} \quad (2)$$

where τ is an independent auxiliary variable, $\mathbf{r} = \{x, y, z\} = \{x_i\}$ is the radius vector in a Cartesian system, $\mathbf{p} = \frac{\mathbf{k}}{|\mathbf{k}_0|} = \{p_i\}$ is the normalized wave vector, $|\mathbf{k}_0| = k_0 = \omega/c$, n is the refractive index for a radio wave in magnetoactive plasma (given by the classical Appleton-Lassen formula), t is the group propagation time, and ω is the radio frequency. For inversion in the E and F regions, collisions in the plasma can be neglected.

[29] There are several other simplifications to realization of the ray-tracing calculations that lead to substantial acceleration of the inversion procedure. The inversion is done in a succession of wedges, from bottom up. When performing the least squares procedure for determining parameters of a current wedge, one can consider parameters of all underlying wedges as established and fixed, so it is necessary to recalculate iteratively only those segments of raypaths of the echoes reflected within the current wedge that lie inside it. Furthermore, echoes that were detected by the dynasonde definitely represent radio signals that were reflected by the ionospheric structures back to the sounder location, the separation

of transmitting and receiving antennas being negligible. So it is reasonable to assume that downward propagation from the turning point was along the same raypath as for upward propagation. This reduces most ray-tracing calculations to one half of the full ray trajectory, starting at the sounder location and reaching the uppermost point. Measured angles of arrival of the echoes serve as initial conditions for this calculation.

5. Least Squares Optimization Procedure

[30] The wedge-stratified ionosphere model requires only a standard and relatively simple plasma density distribution within individual wedges. Assuming that the parameters of all underlying wedges have already been found, there are three parameters that fully control this distribution for a current wedge: the vertical position h_{i+1} of its upper boundary (of the next frame plane, corresponding to plasma frequency $f_{p\ i+1}$) and the orientation of this plane (characterized by horizontal components of its normal vector $n_{x\ i+1}, n_{y\ i+1}$). Many echoes are usually found by the dynasonde data analysis procedures to be reflected within each wedge. For inversion purposes we require at least 10 such echoes. If necessary, the standard plasma frequency step employed by the NeXtYZ algorithm (0.05 MHz) is increased for specific wedges to accommodate more echoes. In cases when the number of echoes exceeds 50 for a minimal plasma frequency step, only the 50 highest-amplitude echoes are actually used, to avoid an unreasonable computational load.

[31] Each of the echoes is characterized by a set of physical parameters determined by the dynasonde preparatory data analysis procedure. These are (1) amplitude, (2) polarization, (3) two angles of arrival θ_j and φ_j , (4) the stationary phase group range R'_j , (5) an average phase R_j^* , and their respective error estimates. All, except for the phase, are used by NeXtYZ. The decibel value of the amplitude is used as a weighting factor in some averaging and selection operations. Polarization determines (as “ordinary” or “extraordinary”) the appropriate expression for the refractive index in the ray-tracing calculations for the echo. The angles of arrival provide initial conditions at the ground for the ray equation set and determine two other useful characteristics, the average angles of arrival (Θ_{i+1} and Φ_{i+1}) for echoes reflected within a wedge. The set of group ranges is used, without any alterations, in the optimization procedure.

[32] Reflection points for a set of echoes may be distributed arbitrarily within the wedge space. If the plasma distribution is smooth, the reflection points tend to be located along a line, not necessarily straight, where the independent variable among members of the set may be frequency or time or some mixture of the two. In the presence of small-scale structures (a very typical situa-

tion), the reflection points are spread in space (in accord with the impression given, in virtual space, by Figure 1). NeXtYZ does not impose artificial restrictions on the spatial distribution of the reflection points, provided that ray tracing is able to reproduce it accurately enough. If the calculated position of an echo reflection point appears outside (below) the current wedge, this echo dropped from the optimization process.

[33] Both group ranges R'_j and angles of arrival (θ_j, φ_j) of the echoes reflected within the current wedge are sensitive to the parameters of the current wedge ($h_{i+1}, n_{x\ i+1}, n_{y\ i+1}$). A purpose and the main idea of the optimization procedure is to determine best estimates for $h_{i+1}, n_{x\ i+1}, n_{y\ i+1}$, by minimizing (in successive iterations, rather than in combination) two quantities:

(1) the residual $\Delta R'_{i+1} = \sqrt{\sum_j (\rho'_{i+1,j} - R'_{i+1,j})^2}$ for calculated (ρ'_j) and measured (R'_j) values of the echo group range and (2) the distance between the sounder location (origin of the coordinate system) and the “ground return point” for the ray launched from the coordinate origin at the angles Θ_{i+1} and Φ_{i+1} defined above. The second component of the optimization procedure increases its sensitivity to the tilts of ionospheric layers; it is justified by the requirement that the tilt structure of the ionospheric layer necessarily provides the conditions that the echoes return to the sounder location. In the real ionosphere, small-scale irregularities facilitate compliance with this condition for the whole set of detected echoes. The present version of the wedge-stratified ionosphere model does not include any small-scale structures, and the automatic return to the sounder location is not guaranteed for all echoes, so we apply the minimization condition to a ray with the average measured direction of arrival for the echoes within the wedge. This is the only ray for which the descending branch of its raypath is calculated completely and explicitly during iterations.

[34] As remarked, the two components of the optimization procedure are not explicitly combined in NeXtYZ; we find it more effective to implement them alternately, at successive steps of the iterative process for the working wedge. In this arrangement, a level of stability of both parts of the optimization procedure is achieved that makes unnecessary any application of special regularization methods.

6. Underlying Ionization and Valley

[35] One generic problem of ionospheric radio sounding is the lack of observational data about the plasma density distribution below the minimum plasma frequency detected by the ionosonde (by echoes of either ordinary or extraordinary polarization) and within the *E-F* valley. Information about such “unseen” plasma densities is necessary for accurate inversion of the parts of the

plasma density profile that are directly observed. At most, a very few parameters of unseen regions can be obtained from the observations (including combined use of oppositely polarized echoes), far fewer than their shape requires, so recourse must be made to appropriately parameterized models.

[36] The most up-to-date models available for the twilight/night E region and the daytime E valley are those developed recently by *Titheridge* [2000, 2001, 2003a, 2003b]. The models are physics based and have been validated by comparison with available experimental data, including incoherent scatter radar and in situ measurements (the validation details may be found in the references given). Input parameters for the models are geographic latitude, day of year, local time, Kp index, and $F_{10.7}$ index. Outputs are profiles of plasma density in required altitude segments above 80 km.

[37] NeXtYZ does not use the model profiles directly and blindly. A set of adjustment coefficients (absent in the models themselves) is introduced by the inversion algorithm and is applied dynamically to the models. The adjustments may include stretching (shrinking) along the plasma frequency axis, stretching (shrinking) along the real height axis, and adjustment of slope. In the valley case, the scaling coefficients are applied in a way that does not distort the width-to-depth ratio of the valley model. Specific values of the scaling coefficients are obtained by the optimization procedure together with parameters of the first wedge above the modeled region.

7. Error Estimates for the Electron Density Profile

[38] The basic echo parameters from the dynasonde are overdetermined in a least squares process that yields their formally dependent errors [Pitteway and Wright, 1992]. Examples of the error sources subsumed in this way are (1) high-order deviations from an incident plane wave assumption; (2) higher-than-second-order variations of echo phase with frequency and time; and (3) marginal (~ 10 dB) signal/noise, although >30 dB is common. Such errors are usually quite small, and while it would be possible to propagate them through the NeXtYZ process, this alone would neglect the generally more significant uncertainties attributable to representation of medium- and small-scale irregularities in the ionosphere. To avoid encumbering the process with ineffective formal error propagation, we instead elect to give attention to the inaccuracies of representation of the real ionospheric layer by the resulting WSI model.

[39] Error estimates that express uncertainties of the inversion procedure itself are a natural product of NeXtYZ. Success of the optimization is indi-

cated by a final value of the minimized residual $\Delta R'_{i+1} = \sqrt{\sum_j (\rho'_{i+1,j} - R'_{i+1,j})^2}$ pertaining to wedge i .

The smaller $\Delta R'_{i+1}$, the more accurate is the solution. However, the minimum value of the residual practically never reaches zero. It may be considered as a statistical characteristic of the remaining local (wedge i) discrepancy between the data set and the solution. This is a ready estimate of the local inversion error. One needs only to convert this estimate from virtual range into real height. NeXtYZ uses the following scaling coefficient, based on the averaged measured group range $\langle R'_j \rangle_{i+1}$ and on the available solution for real height h_{i+1} , to translate the group range uncertainty $\Delta R'_{i+1}$ into a real height error estimate, Δh_{i+1} :

$$\Delta h_{i+1} = \Delta R'_{i+1} \cdot \left[(h_{i+1} - 80 \text{ km}) / \left(\langle R'_j \rangle_{i+1} - 80 \text{ km} \right) \right].$$

[40] We give several examples showing that error estimates on the plasma density profiles, introduced as described above, display quite expected behavior. Note that plotted error bars are represented along the height axis, because that is the dependent variable in this inversion problem. Error estimates along the plasma density axis, of more practical use (e.g., in assimilative modeling) are easily obtained since the plasma gradient is known throughout the profile.

[41] Figure 3 presents two dynasonde ionograms and corresponding plasma density profile inversion results to compare relatively quiet and well-defined ionospheric conditions over Bear Lake Observatory, Utah, on 3 December 2005 at 2335 UT and moderately disturbed conditions over the European Incoherent Scatter (EISCAT) Tromsø observatory on 30 December 2005 at 1230 UT. One can see that the error bars are substantially larger in the second case, indicating increased spatial variability of the ionospheric plasma density.

[42] Figure 4 demonstrates examples of the reaction of NeXtYZ error estimates to occasional blunders of the process by which traces are selected for inversion. Trace selection is a part of the dynasonde data analysis suite DSND that prepares input information for subsequent analyses, including NeXtYZ. All automated profile inversion methods encounter similar problems occasionally, and most methods either fail completely or produce incorrect results without any indication of an introduced fault. The standard NeXtYZ reaction is a dramatic increase of error bars for the respective part of the profile. This feature of the inversion algorithm makes quality control of its products very straightforward, which is important for operational applications.

[43] Summarizing properties of the error calculation approach implemented in NeXtYZ, let us notice that error

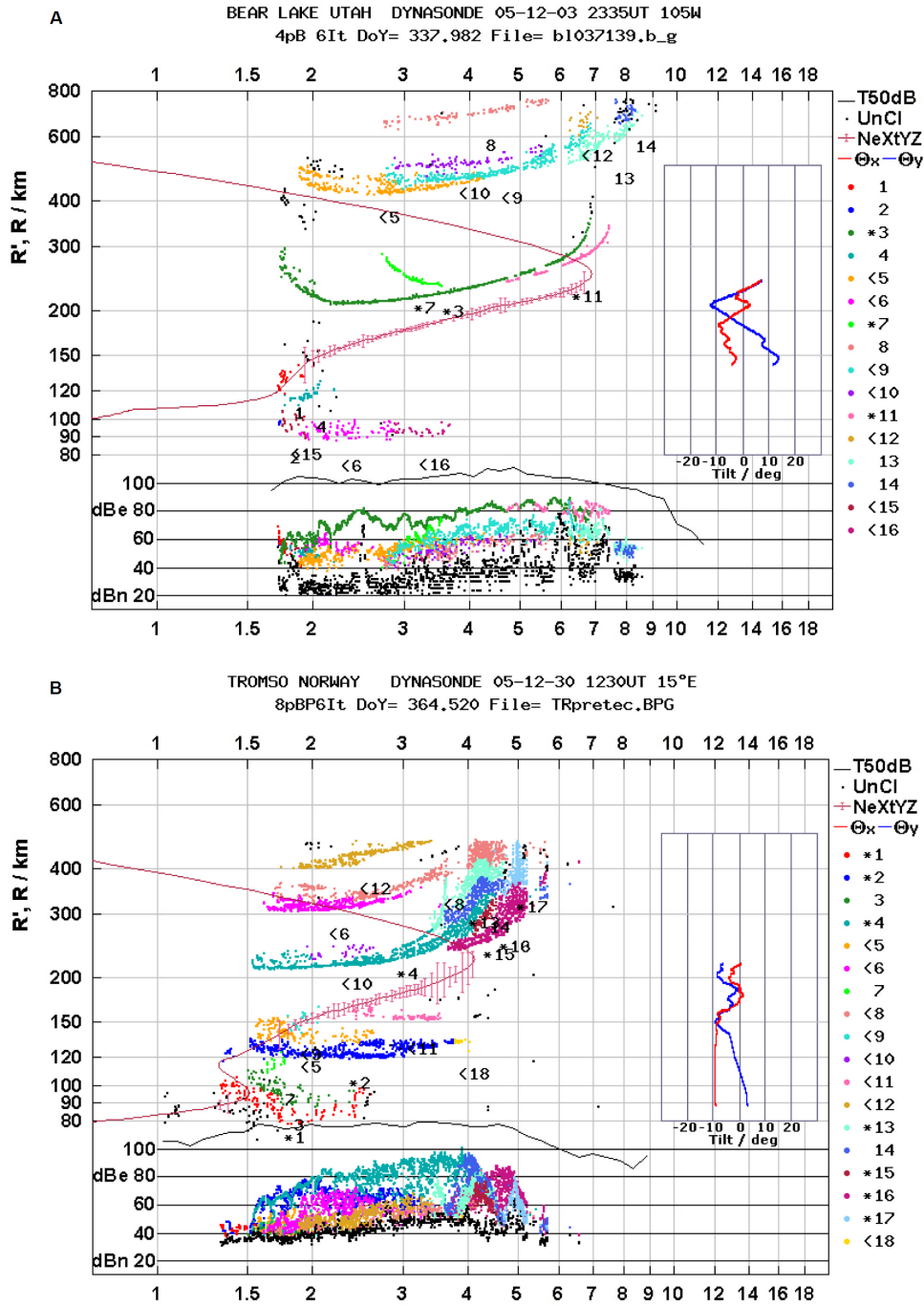


Figure 3. Ionogram “images” in (part of) the standard dynasonde presentation format (other plots showing Doppler, echolocations, polarization, and an error parameter are omitted). Echo group range versus radio frequency appear in log-log coordinates; colors denote echo classes or “traces.” Decibel amplitudes of echoes (color) and noise (black) and a “top 50” amplitude calibration curve occupy the bottom plot. The inset, sharing the same h coordinate with the NeXtYZ vertical profile, $h(f_p)$, shows the local tilt angles in the magnetic meridian (red) and zonal (blue) vertical planes. Error estimates on the profile (a) are small in a quiet ionosphere and (b) become larger in the presence of “spread F_2 .”

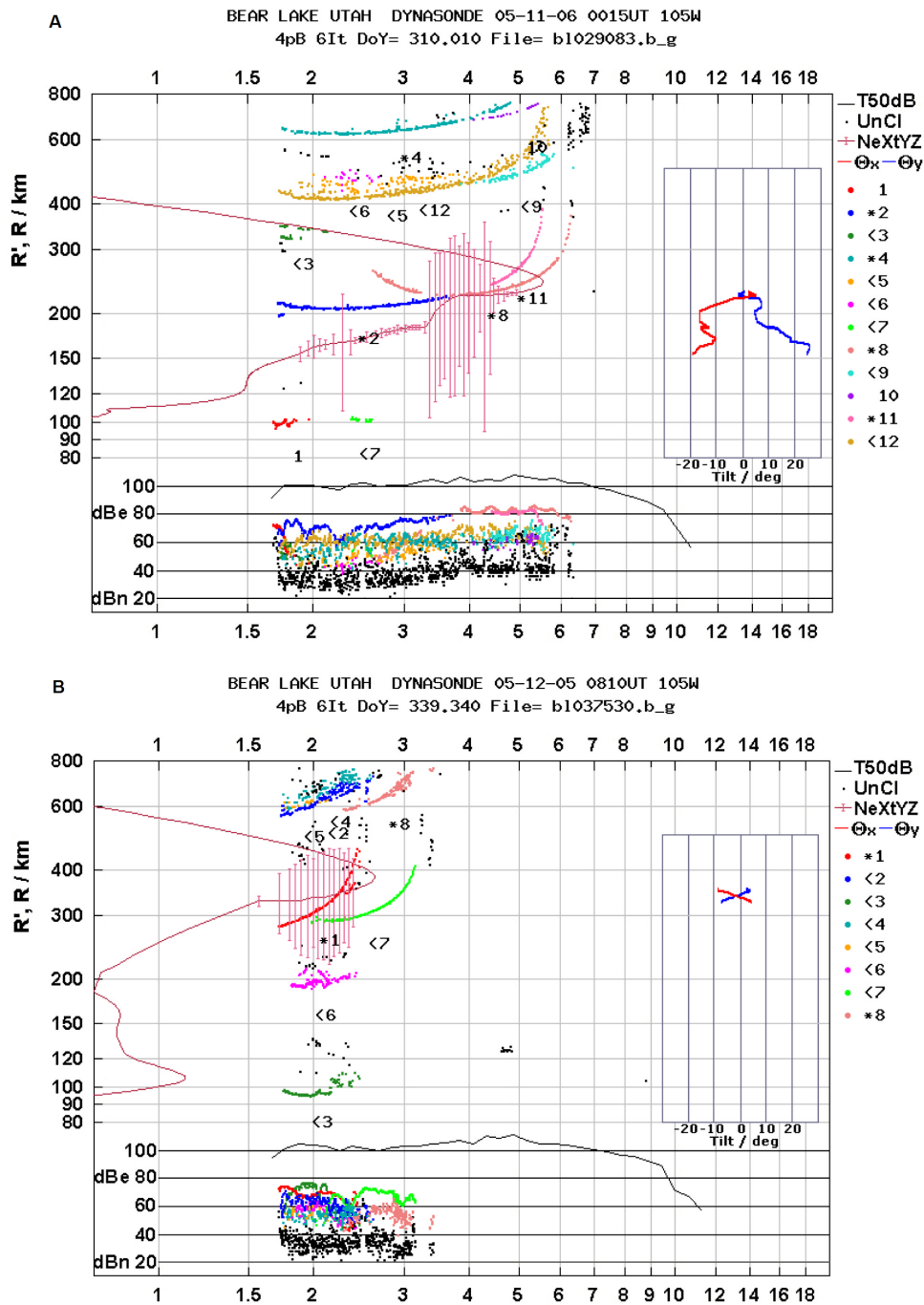


Figure 4. Behavior of NeXtYZ when presented with “blunders” committed by the trace selection algorithms. (a) Trace 4 and the third and “multiple” echoes of F region O trace 2, wrongly enabled for use by NeXtYZ. Both traces contribute to the profile; large error estimates result from O and X contradictions in their region of overlap. (b) Trace 8 (second echoes of F_x trace 7) wrongly enabled instead of trace 7. NeXtYZ obtains an incorrect profile but with entirely reasonable errors.

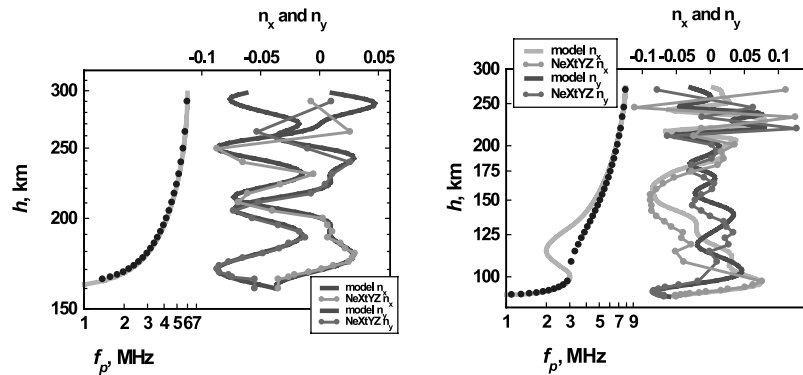


Figure 5. Results of NeXtYZ inversion with a data set simulated for (left) nighttime conditions (only a parabolic F layer is present) and (right) daytime conditions. The WSI model used for simulation is represented by solid lines without data symbols. The NeXtYZ vertical profile $f_p(h)$ and altitude dependence of two components of the normal vector \mathbf{n} are shown by lines with solid circles. For the daytime case, inversion was done without accurate modeling of the valley, under the assumption of monotonic profile. Significant biases of the NeXtYZ solution are caused only by the inadequate valley model.

estimates obtained by this method are specific to the particular ionogram and are even specific to the particular part of the produced profile. Note also that in NeXtYZ many echoes (usually several tens) contribute to the error estimate for every wedge, so that the obtained estimate tends to Gaussian statistics. Both of these features by NeXtYZ conform to the stipulations of modern data assimilation techniques based on the Kalman filter approach.

8. Validation of the Full Three-Dimensional Algorithm

[44] The full version of the NeXtYZ algorithm described in the previous sections has been tested with simulated data sets. The simulation procedure starts from specification of an undisturbed vertical $f_p(h)$ profile (a model consisting of parabolic segments). The profile determines the vertical positions for a sequence of frame planes in the WSI model. Then, variations of orientation of the frame planes are set, according to a chosen (for example, an AGW-like) disturbance model. Low-amplitude ($\Delta N/N \sim 0.2\%$) small-scale (1–2 km) irregularities are superimposed with the model large-scale plasma distribution for the specific purpose of conforming to the usual ionospheric “quiet state.” Finally, multiple three-dimensional ray-tracing calculations are performed with some small step in frequency to simulate ionogram acquisition for raypaths starting and terminating at the origin point on the ground. The final result is a realistic collection of echoes with calculated values of amplitudes, group ranges, and angles of arrival.

[45] These simulated echo parameters are provided to NeXtYZ as input information. Running the inversion

procedure with the simulated data, we then compare its results with the model vertical $f_p(h)$ profile and the model altitude dependence of two components of the normal vector \mathbf{n} (see Figure 5). Tests using this procedure have confirmed good performance of the full NeXtYZ algorithm. Restoration of the vertical $f_p(h)$ profile is always satisfactory, the limitation in daytime conditions being (as for all inversion methods) its dependence on the quality of the E - F valley model. Significant errors in the components of the normal vector \mathbf{n} occur mainly where the total gradient of plasma density is small (e.g., near the F layer maximum in the examples shown in Figure 5) and again as for the profile height in the valley region where tilt information is absent. The right plot of Figure 5 illustrates another property of the algorithm: It is stable even with relation to such major disturbances as an inadequate valley model.

9. NeXtYZ Lite

[46] The full-scale NeXtYZ algorithm is computationally demanding, which suggests the utility of a “lite” version which assumes constant (but not necessarily the same) tilts in several broad regions (the E and F layers). The tilts are determined in the beginning of the inversion procedure on the basis of the averaged angles of arrival of the radio echoes pertaining to each specific region. A smooth transition between parameters of the E region and F region tilts is assumed to occur in the E - F valley. Thus only the vertical positions of the WSI model frame planes, but not the components of their normal vectors, are unknowns in the optimization procedures of NeXtYZ Lite. All other properties of the inversion procedure

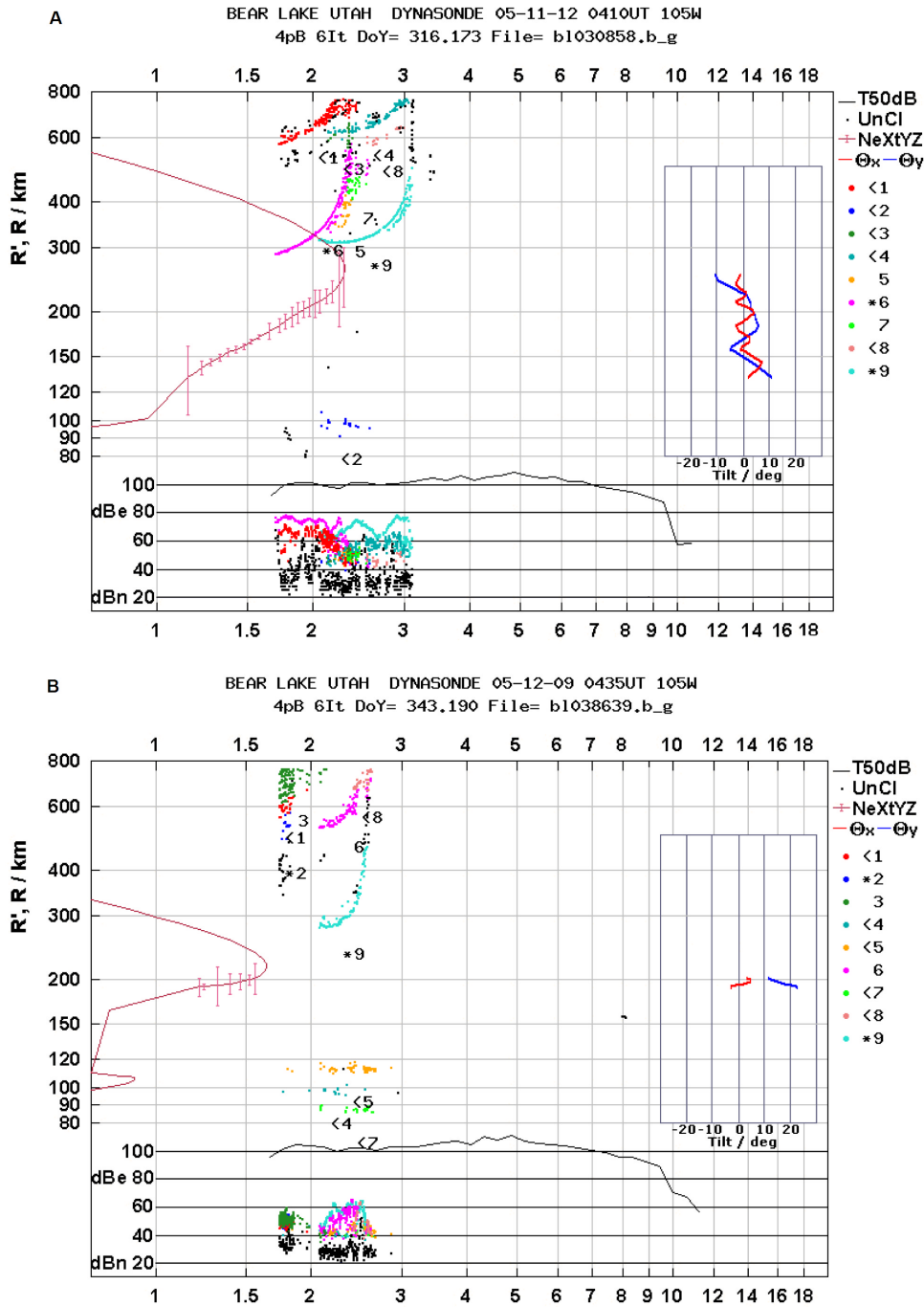


Figure 6. Echoes of extraordinary polarization (a, b) help to constrain the *Titheridge* [2003b] nighttime *E* region model and (b) provide the only information for the *F* region in the absence of echoes of ordinary polarization.

described in the previous sections are common to the full-scale and lite versions of NeXtYZ. In particular, all ray-tracing calculations are three-dimensional: Measured

echo angles of arrival are used as initial conditions in these calculations, and the error bars are defined in the same way.

[47] Despite the coarse resolution of NeXtYZ Lite in describing the altitude dependence of ionospheric tilts, compared with the full-scale NeXtYZ, it still yields results not available from other $f_p(h)$ inversion algorithms: Average tilts of the E and F layers and calculated real-space locations of the reflection points for all echoes are obtained. There are also at least four features characteristic of NeXtYZ Full, preserved in NeXtYZ Lite, that provide higher-quality information about the vertical $f_p(h)$ profile than any one-dimensional algorithm.

[48] 1. Treatment of magnetic field effects is free of the biases caused by assumption of vertical propagation; the simplified approach satisfies the basic requirement identified by *Wright* [1990] that tilts must be approximated for correct choice of propagation (“dip”) angle when echoes of O , X polarization are combined in the analysis to aid valley and night E corrections.

[49] 2. Ordinary and extraordinary echoes are used equally in NeXtYZ, allowing better characterization of underrepresented ionospheric regions (see Figure 6).

[50] 3. NeXtYZ uses state-of-the-art models for underlying ionization and the E - F valley.

[51] 4. NeXtYZ provides extensive statistical information for estimation of $f_p(h)$ profile errors.

10. Real-Time Testing of NeXtYZ

[52] NeXtYZ has been extensively tested with real-time data from existing dynasonde stations starting in December 2004. On 8 March 2005, NeXtYZ Lite became a standard part of the dynasonde’s automated data analysis program DSND. NeXtYZ Full gained this status in November 2005. All other dynasonde data products are now based on results of the NeXtYZ inversion. Throughout the testing period, analysis results have been accessible at the Dynasonde Ionosphere Explorer Web site, <http://www.ngdc.noaa.gov/stp/IONO/Dynasonde/>. During most of the testing period, parallel calculations have been made with POLAN, and results produced by both algorithms have been displayed for comparison in real time. These results are available for retrospective comparison through the dynasonde database at the Web site.

[53] By the time of submission of this paper (March 2006), approximately 175,000 ionograms had been processed by this method. This long-term test series demonstrates another important feature of the NeXtYZ algorithm: It is much more robust against trace selection blunders and bad data. Ionospheric profiles obtained by NeXtYZ are significantly more uniform and stable against bad or insufficient data than those from POLAN.

[54] Optimization of the NeXtYZ code has been performed side by side with its development. By now, analysis of a typical dynasonde ionogram with the

NeXtYZ Full profile inversion algorithm takes about 2.5 min on a standard 3.4 GHz Pentium 4 processor PC. With NeXtYZ Lite, the average analysis time is only 0.5 min. This performance makes both the lite and full NeXtYZ versions appropriate not only for scientific studies but also for modern operational applications.

11. Conclusions

[55] Horizontal plasma density gradients are pervasive in the ionosphere, and they occur throughout a wide spectrum of spatial scales and magnitudes. At the heart of ionospheric space weather, they have important practical significance, causing radio scintillations, GPS errors and failures, and navigation and signal-bearing errors. They are at the heart of ionospheric science also, as both a contributing cause and the common result of plasma instabilities and irregularities. Ionospheric sounding, with its special “reflection level selectivity” throughout the low- to high-frequency bands, is potentially one of the most sensitive diagnostics of these gradients; NeXtYZ is the first realization of this potential.

[56] NeXtYZ replaces POLAN for electron density profile inversion as the “industry standard.” Basic development of the core NeXtYZ (full 3-D) algorithm is completed. It has been tested with electron density distributions described by the wedge-stratified ionosphere (WSI) model and simulated ionograms. Parameters of the WSI in model calculations are reproduced satisfactorily. It also has been tested since December 2004 with real-time data from existing dynasonde installations.

[57] Two main circumstances have enabled implementation of NeXtYZ: First, the dynasonde analysis program DSND provides a high density of data points, typically several thousand echoes per ionogram, each supplied with accurate physical parameters. This permits solution of the optimization problem for each plasma density “wedge” with high accuracy. Second, the modern PC quickly performs ray-tracing calculations. Real-time processing of ionogram data using NeXtYZ in reasonable time (0.5–2.5 min) does not require expensive hardware solutions.

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