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Validation of electron density profiles derived from oblique ionograms over the United Kingdom

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Abstract. Inversion algorithms are available to derive the vertical electron density profile at the midpoint of an oblique sounder path. The techniques open up the possibility of monitoring the ionosphere at otherwise inaccessible locations, such as over sea or inhospitable terrain. A new method of monitoring the ionosphere based on radio tomography can be used to create two-dimensional images of electron density. The results in this paper compare midpoint profiles derived from oblique ionograms with corresponding profiles obtained from tomographic images of electron density and from a vertical ionospheric sounder. The comparisons illustrate the oblique sounder inversion technique and its inherent limitations. The results provide useful information on the complementary nature of the separate ionospheric measurement techniques and have implications for the use of these measurements as inputs to real-time ionospheric models.

1. Introduction

Vertical ionosondes are radio sounders that sweep the HF frequency range and generate ionograms depicting the group path as a function of frequency. By a process of inversion [e.g., *Titheridge*, 1985] these can be used to derive, with some ambiguity, the ionospheric electron density profile below the *F* region peak. Vertical ionosondes have been used extensively in ionospheric research [*Reinisch*, 1986] and HF frequency management [*Shukla et al.*, 1997]. However, to date, oblique ionosondes [e.g., *Barry and Fenwick*, 1969], where the ionosonde is operated bistatically, have not yet been so widely used. These instruments also generate ionograms, this time of the oblique group path as a function of frequency. For a single hop, inversion of the oblique ionogram gives an approximation to the electron density at the midpoint between the transmitter and receiver.

A number of strategies used to invert oblique ionograms have been reported in the literature. An early oblique ionogram inversion method [*Gething and Maliphant*, 1967] converted the oblique ionogram to a vertical ionogram using Martyn's equivalent path theorem. The vertical ionogram was then inverted using an established vertical inversion technique. Martyn's theorem assumes that the Earth and ionosphere are flat, so that the inversion technique fails on long oblique paths. The method proposed by *Reilly and Kolesar* [1989] solved simultaneously the equations for the reflection height and the elevation launch angle. The method assumes spherical symmetry in the ionosphere, neglects the geomagnetic field, and anticipates that the absolute value of group delay between transmitter and receiver is known. In a study of the inversion of synthetic oblique ionograms, *Phanivong et al.* [1995] considered the Reilly and Kolesar technique to be robust and reasonably accurate compared to other techniques. In consequence, it has been applied here to actual experimentally derived oblique ionograms.

Very few examples of validation of electron density profiles derived from oblique ionograms have appeared in the open literature. One explanation for the unpopularity of oblique ionogram inversion is the necessity of having the transmitter and receiver time-locked to a common source if the true height electron density profile is to be extracted. However, with the advent of time locking using the Global Positioning System (GPS), oblique sounders may become more widely used for ionospheric research.

The deployment of ionospheric sounders, and subsequent inversion of the observations to electron

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density profiles, provides the potential for updating ionospheric models in near real time. Whereas a vertical sounder provides measurements at a single location, signals from an oblique sounder transmitter can be received at a number of locations. The use of several transmitters and receivers thus has the potential to provide ionospheric profiles from many midpoints. In this way, the ionosphere can be monitored over the sea and other terrain where it is not practical to deploy vertical sounders, so that many more potential updates can be made to an ionospheric model.

The question arises as to the accuracy of the derived midpoint electron density profiles. One obvious approach is to set up an oblique link with a midpoint over or close to a vertical ionosonde. Comparison of the electron density profiles derived from the two techniques yields a useful validation of the oblique inversion method.

An alternative strategy is to compare the oblique ionogram–derived profile with that derived from tomographic techniques. Ionospheric tomography can image the complete electron density profile, both below and above the *F* layer peak, over large spatial regions [*Kersley and Pryse*, 1994; *Raymund*, 1994; *Mitchell et al.*, 1997]. Measurements of the line integral of electron density, known as total electron content or TEC, are determined for a large number of intersecting transionospheric paths between a satellite and a chain of ground-based receivers. These TEC measurements are inverted in a reconstruction process to produce a tomographic image. A number of reconstruction algorithms have been compared by *Raymund* [1995] and more recently by *Pryse et al.* [1998]. The absence of near-horizontal ionospheric ray paths results in missing information on the vertical structure of the plasma density in the tomographic image. However, previous work has demonstrated the usefulness of vertical sounding ionosondes in providing this information as an aid to the tomographic imaging process [*Kersley et al.*, 1993; *Heaton et al.*, 1995].

The results presented in this paper compare midpoint electron density profiles derived from oblique ionograms with profiles obtained from a vertical ionosonde and ionospheric tomography. These comparisons are made to assess the viability of the oblique ionogram inversions and hence the potential for assimilating the resulting profiles into near–real-time ionospheric models.

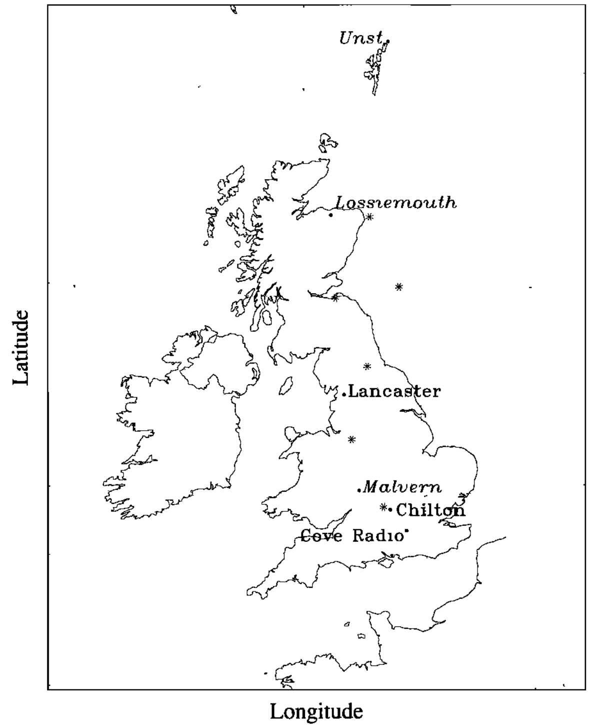


Figure 1. A map showing the locations of the IRIS receivers (italics), the HF transmitters at Lancaster and Cove Radio, and the vertical sounder at Chilton. The asterisks indicate the position of the midpoints for the six oblique paths.

2. Experiment

Three oblique sounder receivers, located at Malvern (52.1°N, 2.3°W), Lossiemouth (57.7°N, 3.3°W), and Unst (60.8°N, 0.8°W), have monitored signals broadcast by the transmitters at Cove Radio (51.3°N, 0.8°W) and Lancaster University (54.0°N, 2.8°W) from October 1997 to May 1999 (Figure 1). These HF oblique sounders, known as Improved Radio Ionospheric Sounder (IRIS), were developed by *Arthur et al.* [1997]. The IRIS receiver sweeps a locally generated phase-continuous replica of the transmitted signal from 2 to 30 MHz at a rate of 100 kHz per second. This locally generated signal is mixed with the received signal, and the beat frequency is analyzed to give the time delays of the modes as a function of frequency [*Poole*, 1985]. When the receiver and a compatible transmitter are deployed with the capability to synchronize to a common time source, such as the GPS system, the absolute path delay of the transmitted signal can be calculated.

The remote sites were connected to a telephone line allowing oblique ionograms to be downloaded in near real time. In addition, changes could be made to the operation as required. These observations have provided a large database of oblique soundings over ground ranges from 140 to 1100 km. An ionogram could be recorded every 5 min with up to 288 ionograms recorded each day.

To test the accuracy of the *Reilly and Kolesar* [1989] method, oblique ionogram inversions were performed for the short Cove Radio to Malvern path. This path was able to take advantage of the vertical ionospheric sounder at Chilton (51.7°N, 1.3°W), only 20 km away from the oblique midpoint (Figure 1). The Chilton sounder routinely made measurements every 30 min, and true height electron density profiles were derived using the polynomial analysis method (POLAN) [*Titheridge*, 1985], with the default *E-F* valley. It should be noted that as this was a relatively short oblique path (ground range of 140 km) the conclusions drawn may not be applicable to much longer paths where, for instance, the assumption of spherical symmetry in the oblique inversion method may not hold. Nonetheless, the method has been tested where the assumptions should hold with some degree of certainty.

A chain of five tomographic receivers spanning the length of the United Kingdom was deployed by the University of Wales, Aberystwyth, from October 1997. These receivers, located at Dartmouth (50.2°N, 1.1°W), Aberystwyth (52.5°N, 4.1°W), Hawick (55.4°N, 2.8°W), Lossiemouth, and Unst (Figure 2), monitored radio transmissions from the Navy Ionospheric Monitoring System (NIMS) satellites. The phase-coherent transmissions on 150 and 400 MHz were monitored to provide a measure of the variation of TEC along the satellite pass. At the time of deployment of the tomographic receivers the satellite system, formerly known as the Navy Navigational Satellite System (NNSS), comprised four operational satellites in circular polar orbits at an altitude of approximately 1100 km. The tomographic reconstruction method used in the current analysis has been described by *Pryse et al.* [1998] and is a refinement of that proposed by *Fremouw et al.* [1994]. Tomographic images, spanning some 20° of latitude, have been reconstructed from measured TEC, with additional information from the vertical ionosonde at Chilton being incorporated to aid accurate reproduction of the vertical ionospheric structure.

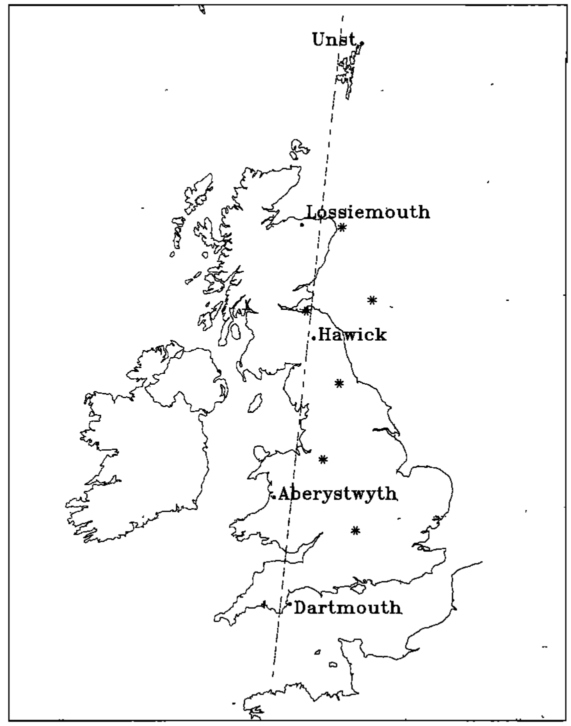
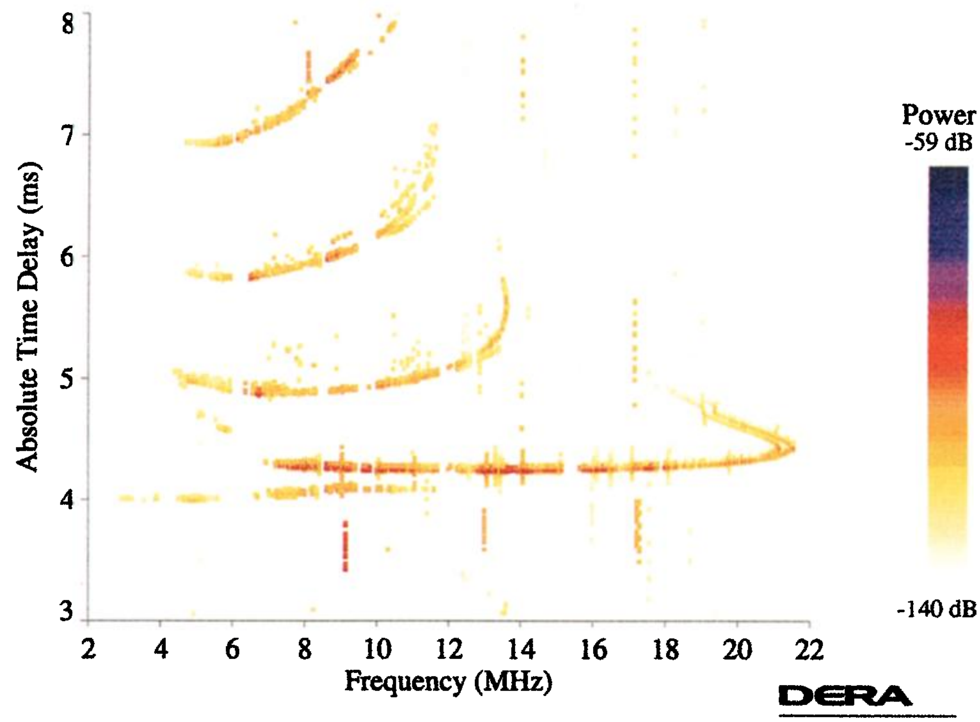


Figure 2. A map showing the location of the tomographic receivers; the dashed line through the receivers indicates an approximate position for the tomographic images. The midpoints of the oblique paths from Figure 1 are also shown.

3. Ionogram Scaling and Inversion Method

A Windows-based analysis suite has been developed to aid the scaling and inversion of oblique ionograms [*Heaton*, 1999]. The user-friendly software was designed to scale ionograms semiautomatically. The algorithm searches from a user-supplied cursor position for echoes in the direction of increasing frequency and automatically scales the echo containing the largest power within a time-frequency window. Having located an echo, the algorithm moves the center of the window by +0.05 MHz but retains the group delay of the previously located echo. If no data point is found within the new window, the frequency is again incremented by 0.05 MHz and the new position of the window is again checked for data. After six consecutive windows where no data are located, the algorithm stops searching; in this way, small gaps in the trace can be "jumped." If gaps are too large, the user simply restarts the search algorithm. This simple, semiautomatic method has the a.



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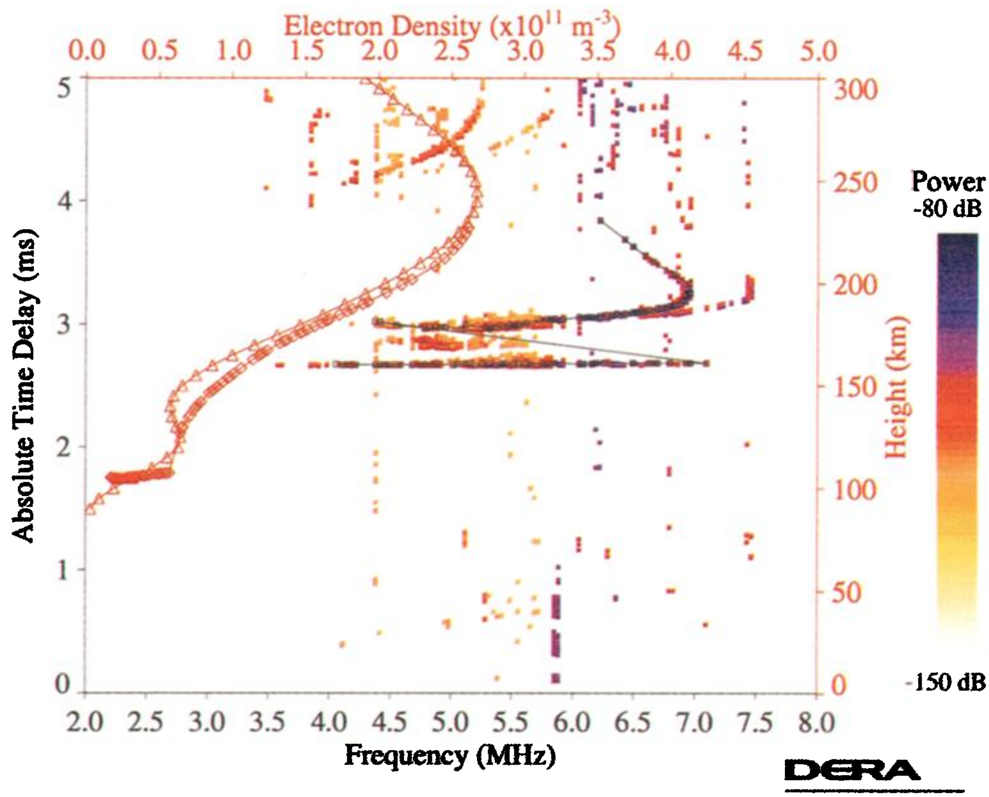

Plate 1. (a) An oblique ionogram for the Oslo to Malvern path (ground range of ~1600 km) collected on December 15, 1998, at 1226 UT. (b) An oblique ionogram for the Lancaster to Unst path collected on April 2, 1998, at 0706 UT. Also shown is the resulting electron density profile (diamonds), along with a tomographic profile (triangles), at the midpoint of the path.

advantage that ionograms are scaled quickly and accurately. The software suite also includes an on-line database to manage the large amounts of data collected from many different oblique paths.

As an illustration of the high-quality oblique ionograms that are obtainable from an IRIS receiver, an example for the Oslo, Norway (63.2°N, 14.7°E), to Malvern path on December 15, 1998, at 1226 UT is shown in Plate 1a; four *F* layer hops are clearly visible. The colors in the ionogram indicate the signal strength of each measurement. Plate 1b is an example from the present experiment. In this case, the ordinary trace of the ionogram has been scaled, and the resulting true height electron density profile is shown along with a profile at the midpoint of the path derived from tomographic methods. (These results will be described in section 4).

It was not possible to invert nighttime oblique ionograms accurately on the Cove Radio to Malvern path as the *E* layer trace tended to have peak values below 2 MHz and hence was not measurable by the IRIS receiver. Thus retardation effects arising from the *E* layer were not accounted for, so that the altitude of the *F* layer was overestimated. Since inclusion of these nighttime profiles would bias the results, they were omitted from the comparisons. This remains an important practical restriction on the inversion technique.

The echoes from the *E* and *F* layers are compressed within the time delay axis when an ionogram is measured over an oblique path. The time resolution for the IRIS receiver is 7.3 μs; this compares to the temporal resolution of the Chilton ionosonde at ~17 μs. As a consequence the definition of the ionogram traces is similar, resulting in similar errors.

4. Results

Electron density profiles derived from the Chilton ionosonde and the Cove Radio to Malvern oblique ionosonde, for coincident times during the daytime, were produced for April 5 and 6, 1998. An example of the vertical profiles for April 5 at 1530 UT is shown in Figure 3. Excellent agreement is found in the shape of the *F* layer, with densities remarkably consistent at most heights. Differences of $\sim 0.1 \times 10^{11}$ m^{-3} can be noted in the profiles immediately above the *E* layer maximum. These differences arise from the absence of an *E*-*F* valley in the profile derived from the oblique ionogram. In addition, this oblique profile falls short of the *F* layer maximum by 10 km. None of the oblique ionograms contained a complete high-angle ray for the *F* layer up to the asymptote, and consequently the inversion process was unable to derive the peak densities for this layer. The radiation patterns from both the transmitter and receiver, the extra divergence associated with the high-angle ray, and the delay dispersion all conspire to preclude probing of the *F* layer peak.

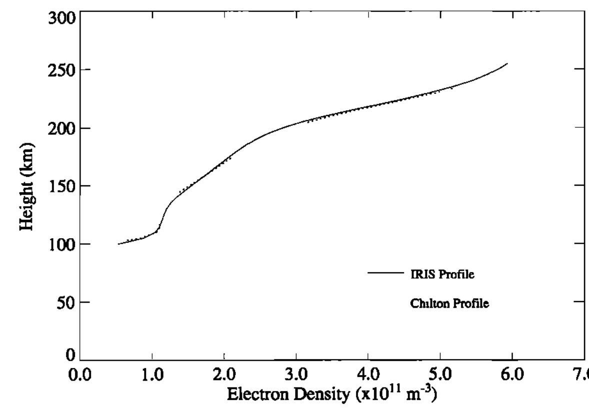

Figure 3. Electron density profiles determined from the Chilton vertical sounder and the Cove Radio to Malvern oblique path for April 5, 1998, at 1530 UT.

To compare the maximum electron densities of the *F* layer, the profiles derived over the 2 day period from the IRIS and Chilton sounders were interpolated onto a 5 km height grid. As the profiles derived from the IRIS observations did not reach the *F* layer peak, but would occasionally fall short by around 20 km, comparisons of the densities at the height of the IRIS maximum density were made (Figure 4). For example, the height at which the densities were compared for the profiles shown in Figure 3 was 255 km. Good agreement can be seen between the two data sets in Figure 4. There is, however, a tendency for the maximum densities derived from the IRIS ionograms to underestimate the densities at the corresponding heights by as much as 5%. Also shown in Figure 4 is the *F* layer peak ionization density, N_mF_2, derived from the Chilton observations. This gives an indication of the differences between the maximum densities derived from the oblique incidence and those at the peak from the vertical incidence measurements, though, again, the differences are small.

The same results are reproduced in a slightly different form in Figure 5, where the densities derived from the Chilton sounder corresponding to the

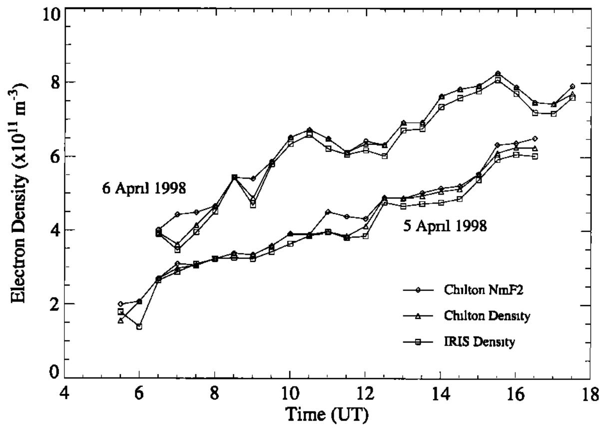

Figure 4. Electron density values determined from the Chilton vertical sounder and the Cove Radio to Malvern path for April 5 and 6, 1998.

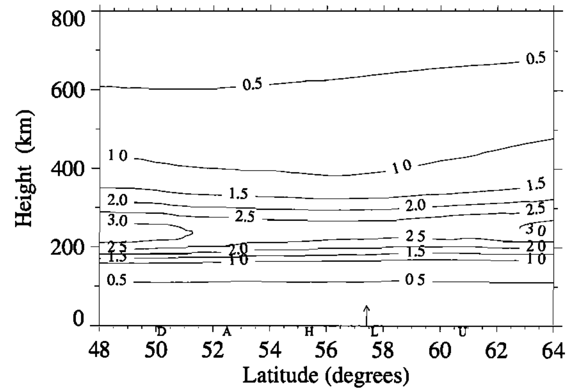

Figure 6. Tomographic image of electron density ($\times 10^{11}$ m^{-3}) for April 2, 1998, at 0704 UT. The position of the arrow indicates the midpoint of the Lancaster to Unst oblique ionogram path.

maximum height of the IRIS profile are plotted against the IRIS maximum density. It can be seen that the IRIS data set, in general, underestimates the magnitude of the electron density even when comparisons are made at the same height. A similar plot (not shown) of the maximum heights indicates that the maximum height derived from the IRIS data falls short of that derived from the Chilton data by around 20 km.

Validation of the inversion method for longer oblique paths requires additional independent observations at the midpoints, where no vertical sounders were located. For these longer paths the electron density profiles have been compared with those derived from tomographic methods. A tomographic image from a satellite pass on April 2, 1998, at ~0704 UT is shown in Figure 6. In this postdawn period the solar-produced ionization is increasing from the south, though a remnant of the poleward wall of the main trough can be seen at the highest latitudes. Between 52° and 62° latitude the electron densities are fairly constant with height, and consequently, the assumption of spherical symmetry required by the *Reilly and Kolesar* [1989] method is applicable. The oblique ionogram recorded at this time for the Lancaster to Unst path (an ionospheric path length of 915 km) is shown in Plate 1b. The ionogram is noisy because of the use of a low-gain whip antenna at the IRIS receiver site. The true height density profile determined from the oblique inversion technique is shown together with a profile from the tomographic image at the same latitude as the midpoint. It is clear that the general shape of the *F* layer indicated by the tomographic profile has been well replicated by the oblique inversion technique. However, the differences in the electron densities at all heights are larger than those on the shorter path (compare Figure 3). The shape and height of the *E* layer do not agree well, and as before, the oblique profile does not extend as far as the *F* layer peak.

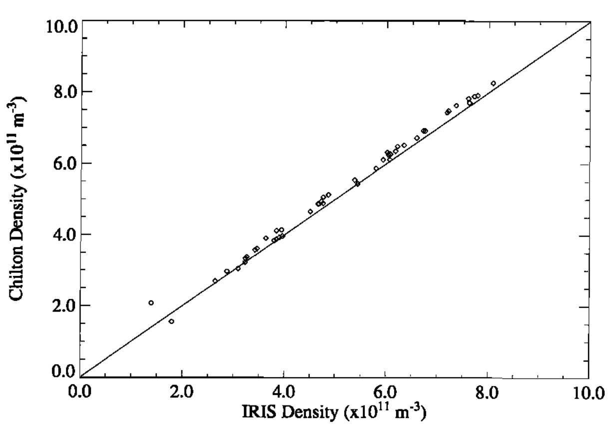

Figure 5. A comparison between the maximum density determined by the Cove Radio to Malvern path and the Chilton density at the corresponding height.

The maximum density at the midpoint of the six oblique paths is compared in Figure 7 to the density at the corresponding height and latitude estimated from three tomographic images. The densities match well, though closer inspection of the profiles shows discrepancies at *E* layer heights, similar to those described above.

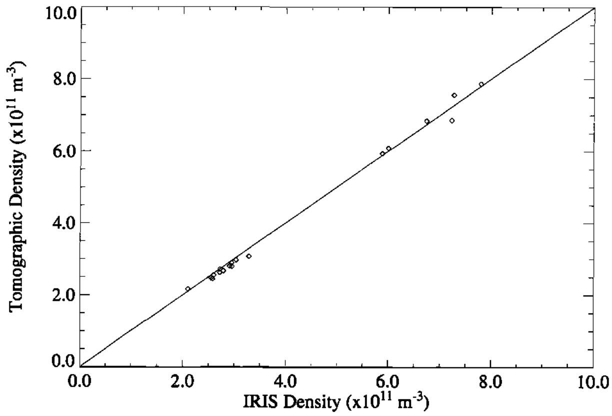

Figure 7. A comparison between the maximum density at the midpoint of a number of oblique paths and the tomographic density at the corresponding height and latitude.

5. Discussion

Comparisons have been made between electron density profiles determined from oblique ionograms and those obtained from vertical ionograms and radio tomography. Extremely good agreement has been found between profiles from the Cove Radio to Malvern path and those from the vertical sounder at Chilton. As this was a relatively short path, further comparisons for longer oblique paths were made using profiles derived from tomographic images. Good agreement was observed at F layer heights, though discrepancies were evident in the E layer (Plate 1b). Several possible reasons for the discrepancies exist. The *Reilly and Kolesar* [1989] inversion method contains a "reentrant" procedure to simulate an E-F valley in the true height density profile. The absence of this procedure in our implementation of the method has resulted in a nonphysical profile of the E layer. Future work aims to include this procedure and thus derive a more realistic E layer profile.

The second reason for the discrepancies relates to errors in the tomographic process itself. N. C. Rogers et al. (Validation of ionospheric tomography by ray tracing and comparison with oblique incidence ionograms, submitted to *Radio Science*, 1999) ray traced through tomographic images, reconstructed using several types of a priori information, to produce synthetic oblique ionograms. The method used in the analysis of tomographic images in the current paper is referred to as "method B" by Rogers et al. They found that the largest mean percentage errors in ionospheric tomography occur in the specification of the E layer where the resulting maximum usable frequency, MUF, was underestimated by around 9%, compared to an overestimate of less than 2% in the MUF of the F layer.

A further explanation for the slight differences observed at F layer altitudes may be the spatial separation in longitude, sometimes by as much as 200 km, between the plane of the tomographic image and the midpoint of the oblique paths. This may be of particular relevance at times of the morning gradient in ionization as in the postsunrise conditions of the example shown in Figure 6.

Results presented in this paper have been determined from oblique ionograms over relatively short paths (<1100 km) where spherical symmetry is a good approximation, with perhaps the exception at times of the dawn/dusk terminator. In order to determine the applicability of the inversion method over longer oblique paths (or where spherical symmetry is known not to occur), further measurements would be needed. It is unclear what the effects of a gradient would be upon the derived electron density profile, but a smearing of the profiles is conjectured.

This preliminary study clearly demonstrates the potential of the oblique incidence technique for deriving ionospheric profiles. However, its limitations and errors are not completely resolved. In comparison with vertical incidence profiles the reasons for any discrepancies are not clear. However, radio tomographic imaging can provide an image of the ionospheric path conditions so that issues like the applicability of spherical symmetry can be assessed with ease. An attractive experiment for the future would involve a midpoint vertical incidence sounder and a tomographic image.

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