Antarctic Science 8 (3): 297–302 (1996)

Toward ionospheric tomography in Antarctica: first steps and comparison with dynasonde observations

J.A.T. HEATON[1], G.O.L. JONES[2] and L. KERSLEY[1]

[1]*Department of Physics, University of Wales, Aberystwyth SY23 3BZ, UK*

[2]*British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK*

Abstract: Total electron content (TEC) measurements obtained at two Antarctic stations over nine months beginning early in 1994 have been analysed as a first step to performing ionospheric tomography. Two receiving systems were deployed at the Faraday and Halley research stations operated by the British Antarctic Survey to monitor signals from a random selection of passes of satellites in the Navy Navigational Satellite System. The resultant measurements of total electron content have been inverted and combined with ionosonde measurements of true height and *fo*F2 to yield two-dimensional contour maps of ionospheric electron density. In spite of the poor geometry of the observations, some 130 satellite passes were found to be suitable for reconstruction using the techniques developed for ionospheric tomography. The contour maps of plasma density have been compared with independent observations of the vertical electron density profile measured by the dynasonde ionospheric sounder located at Halley. An example is presented of a deep trough investigated by the technique, illustrating the potential of the tomographic method for study of an extended spatial region of the ionosphere over inhospitable terrain.

Received 31 January 1996, accepted 11 June 1996

Key words: dynasonde, ionospheric tomography, mid-latitude trough, total electron content

Introduction

The tomographic technique aims to image a parameter in a cross-sectional plane through a medium. It relies on the line integral of the parameter to be known along a large number of intersecting paths in the plane of interest, with the measurements being inverted in a reconstruction algorithm to yield an image of the parameter. If measurements of the line integral of electron density, the so-called total electron content (TEC), are measured along many intersecting ray paths through the ionosphere, then in principle, tomographic images of the electron density can be obtained. This application of the technique was first proposed by Austen *et al.* (1986), and ionospheric tomography has now become an established technique. Recently, reviews of the development of the method have been published by Kersley & Pryse (1994) and Raymund (1994). Ionospheric tomography is particularly suited to the imaging of features like the troughs, blobs and patches that are found at high latitudes. The near-vertical field alignment of these structures means that a limitation to ionospheric tomography arising from the lack of horizontal rays is of lesser importance at high latitudes. In addition, the method yields images with wide spatial coverage from observations at a few ground-based locations, a consideration of importance given the inhospitable terrain at polar latitudes.

The current paper presents the first results from a rudimentary ionospheric tomography experiment performed at two of the BAS research stations between January and September 1994. The resulting contour plots of plasma density have been used to compare the electron densities derived above Halley with completely independent observations made by the dynasonde ionospheric sounder located at this station.

It must be noted that the use of only two ground stations, far apart geographically and not lying in a common meridional plane, represents a stringent test for ionospheric tomography. Indeed, because of the longitudinal separation, the ray paths from satellite to the individual stations do not in fact intersect, so that the assumption of a zonally uniform ionosphere is implicit in the analysis. Furthermore, with only two stations spaced by some 10° in latitude, the ray-path geometry is such that only large-scale features can be investigated. Nevertheless, a successful test of the tomographic method under conditions of such unfavourable geometry represents a powerful demonstration of the potential of the method and provides justification for further work into the study of the ionosphere in inaccessible regions.

Experiment

The tomographic observations were made by monitoring radio transmissions from satellites in the Navy Navigational Satellite System (NNSS). The satellite system at the time of the experiment comprised four operational satellites in near-circular polar orbits at altitudes of approximately 1100 km. The satellites transmit two phase-coherent signals at 150 and 400 MHz. Measurements of the TEC between the satellite and receiver were obtained by measuring the differential carrier phase of the two radio signals reduced to a common

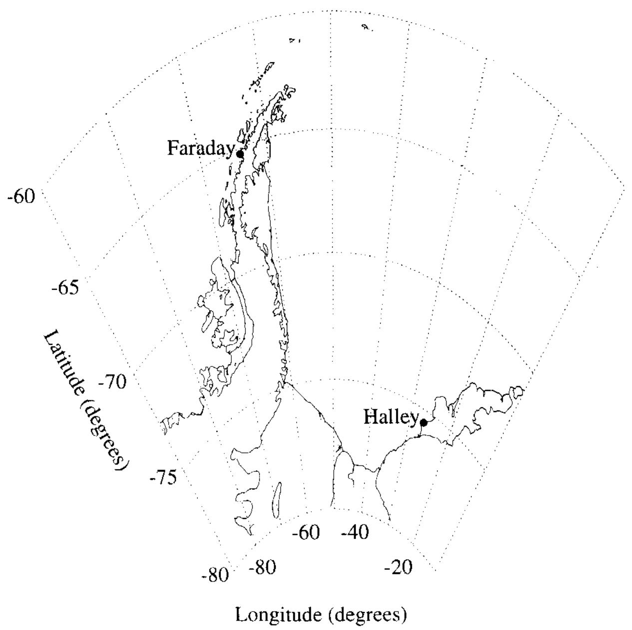

Fig. 1. Map showing locations of the receiving sites and the ionospheric sounders at Faraday and Halley.

intermediate frequency. For the tomographic experiment, two receiving systems were located at Faraday (65.3°S, 64.3°W) and Halley (75.6°S, 26.3°W), respectively. The locations are shown on the map in Fig. 1. Each receiving system was based on a modified JMR-1 commercial navigation receiver and controlled by a laptop computer. Further details of the experimental equipment have been given by Kersley *et al.* (1993).

The satellite receivers were deployed in an automatic mode to monitor a random selection of satellite passes. A total of 1100 satellite passes were recorded simultaneously by both receivers during the period of the experiment. However, due to the large longitudinal separation of the receiving stations, only those passes from satellites orbiting in a meridian between the stations were considered for tomographic analysis, so that the large database was reduced to 130 usable passes.

Ionospheric sounders are in operation throughout the year at both Halley and Faraday. At Faraday, also known as Argentine Islands, an analogue ionosonde records quarter-hourly ionograms, and standard ionospheric parameters are scaled from each hourly sounding (Broom 1984). At Halley, a digital ionosonde known as a dynasonde (Dudeney *et al.* 1982) makes observations every five minutes, from which various ionospheric parameters can be derived, including the range, plasma frequency and horizontal location of each radio echo (Dudeney *et al.* 1995). This spatial information enables the dynasonde data to be used to verify the tomographic densities in the vicinity of Halley.

Analysis

Contour plots of electron density were reconstructed from the simultaneous data recorded at the two ground sites for each of the 130 satellite passes. Processing of the differential phase data yielded slant TEC measurements along the satellite-to-receiver ray paths. Absolute values of slant TEC were estimated by comparing the phase measurements from the two stations using the method proposed by Leitinger *et al.* (1975). The satellite orbits were displaced in longitude with respect to the two stations, so the slant total electron content was measured along a non-vertical plane. To compensate for this longitudinal displacement, a simple geometrical correction was applied to the calibrated slant TEC, to map the observation into the local vertical plane at each station. This correction has been used with success in other tomographic work (Kersley *et al.* 1993), though the longitudinal separations were much less than in the current work.

The iterative reconstruction algorithm used was the Multiplicative Algebraic Reconstruction Technique (MART), which for the ionospheric application requires an initial estimate of the background ionization distribution, as described by Raymund *et al.* (1990). The annular-shaped pixels had dimensions of 15 km in altitude by 0.25° of latitude, with the electron density being assumed constant within each pixel. Three iterations of the MART algorithm were used in the current analysis with a relaxation parameter set to 0.2.

To prevent the resulting electron density plots being biased toward a single initial estimate, a set of initial background ionospheres was used, with each one producing a tomographic reconstruction. The RMS error was then calculated between the computed TEC through each plot and the measured TEC, with the plot yielding the minimum RMS value being taken as the 'best' reconstruction.

The height of the F-layer peak chosen for each initial estimate was taken to be constant over the whole latitudinal range of the grid and was estimated from ionospheric sounding data obtained from the ionosonde at the Faraday station. The true height was estimated using the method of Bradley & Dudeney (1973), a procedure that requires as input the values of the scaled ionospheric parameters M(3000)F2, *fo*E, and *fo*F2. For the current work the hourly values of these parameters were used from the ionosonde located at Faraday. If the values were not available for the approximate time of a satellite pass, the peak height was estimated from the IRI-90 ionospheric model (Bilitza 1990), with appropriate input conditions.

The bottomside ionization profile for the initial estimates was based on a Chapman distribution with three different scale heights, 40, 60, and 80 km, while the form of the ionization above the layer peak was computed using a library of normalized topside shapes (Heaton *et al.* 1995). For the current work 12 topside shapes were used. When matched to the three bottomsides, they yielded 36 different initial estimates

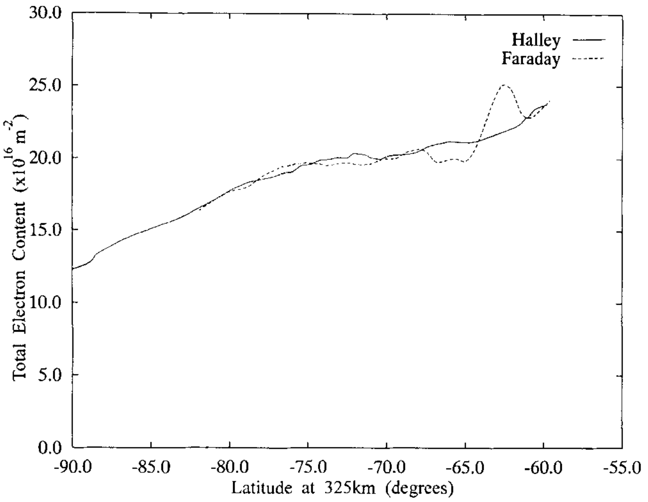

Fig. 2. Equivalent vertical total electron content from both receiving sites for the satellite pass crossing 70°S at 11h13 UT on 10 January 1994.

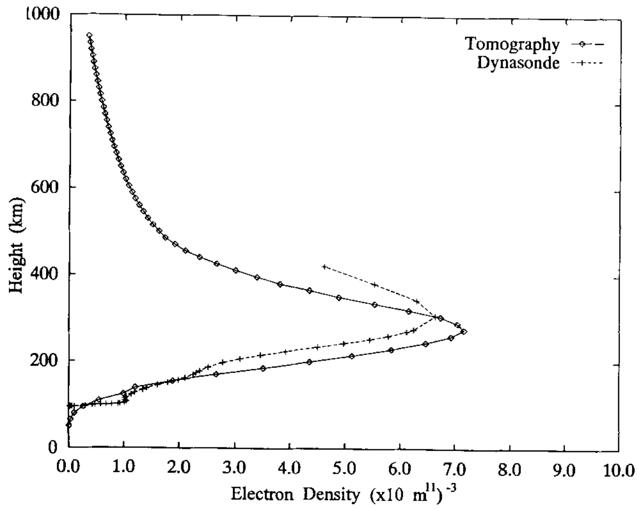

Fig. 4. Comparison of the electron density profiles obtained from the tomographic reconstruction and dynasonde observations above Halley (75.6°S) on 10 January 1994 at 11h13 UT.

of the ionization distribution, all with a common peak height. Finally, a latitudinal gradient of F-region peak density, estimated from the IRI90 model, was applied to the initial estimates, forcing the peak density at the latitude of Faraday to be equal to that determined from the *fo*F2 measured by the Faraday ionosonde.

Results

An example is shown in Fig. 2 of equivalent vertical TEC, obtained by means of a simple geometrical rotation from the slant TEC measured simultaneously at the two sites. This north-to-south satellite pass was monitored on 10 January 1994, with the satellite crossing 70°S latitude at longitude 37.3°W at 11h13 UT. It can be seen that there is close

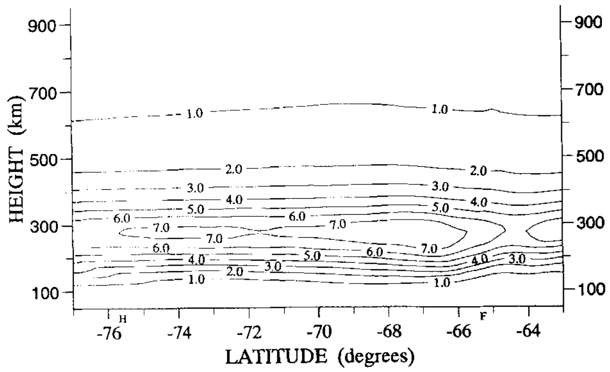

Fig. 3. Contour plot of electron density as a function of latitude and height for the satellite pass around 11:13UT on 10 January 1994. The letters *H* and *F* denote the latitudes of the receiving sites at Halley and Faraday, respectively. Contours of electron density are in units of $10^{11}m^{-3}$.

agreement between the measurements from each site with a gradient in TEC indicating higher electron densities equatorward. The resulting electron density reconstruction for this pass is shown as a function of height and latitude in Fig. 3. Densities in excess of 7.0 x $10^{11} m^{-3}$ at the F-layer peak are observed to extend from ~75°S to 66°S. The discontinuity in the electron density on the bottomside at around 76°S is an artefact of the reconstruction technique and occurs where the receiver at Faraday lost lock from the satellite signal towards the end of the pass. However, the depletion in the peak density near 65°S is *not* a reconstruction artefact; it can be seen from Fig. 2 that the equivalent vertical TEC observed at Faraday shows evidence of a wave-like fluctuation towards the north, and it is this travelling ionospheric disturbance that is manifest in the horizontal structure of the tomographic plot to the north of this station (Pryse *et al.* 1995).

Figure 4 compares the corresponding electron-density height profiles from the two methods. The dynasonde measurement from Halley at 11h15 UT on 10 January has been converted to a true-height inversion profile using the Polynomial Analysis method, POLAN (Titheridge 1985). Also shown in the figure is the vertical electron-density profile through the tomographic plot at the latitude of Halley (75.5°S). There is broad agreement between the general form of the two profiles, which were produced completely independently. The tomographic technique gives the magnitude of the peak ionization to be 7.2 x 10^{11} m^{-3} at 275 km, compared with the dynasonde observation of 6.6 x 10^{11} m^{-3} at 307 km. The scale height of each profile above an altitude of 200 km also compares well. The discrepancies seen in the two profiles are due to a number of factors described below. A limitation of ionospheric tomography is its inability to modify the vertical distribution of the initial estimate due to the lack of horizontal satellite-

https://doi.org/10.1017/S0954102096000430 Published online by Cambridge University Press

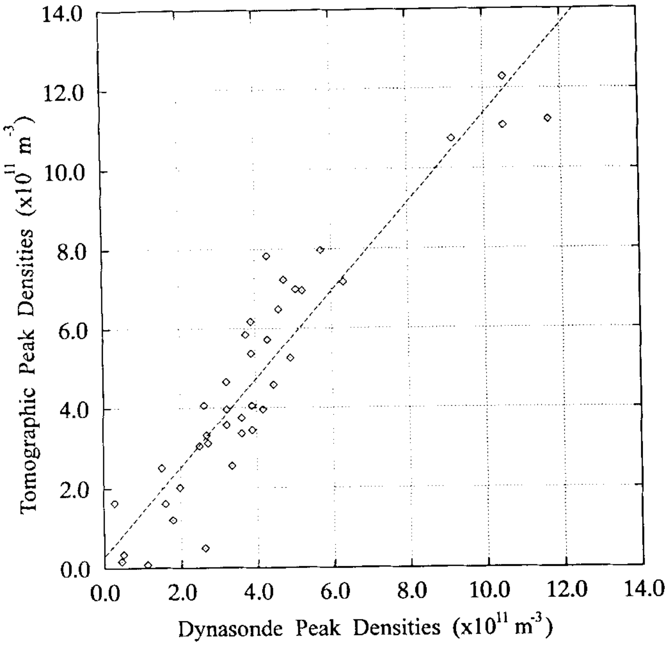

Fig. 5. Comparison of the electron densities at the F2-layer peak above Halley from the tomographic reconstructions and dynasonde measurements.

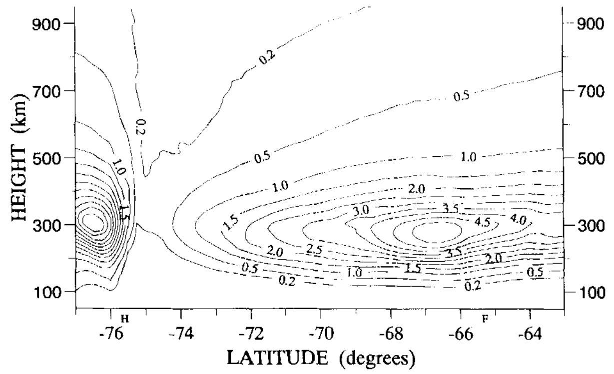

Fig. 6. Contour plot of electron density as a function of latitude and height for the satellite pass at 01h56 UT on 18 June 1994. Contours of electron density are in units of $10^{10}m^{-3}$.

to-receiver ray paths. Consequently, the peak height estimated using the observations recorded by the Faraday ionosonde will be unchanged across the tomographic reconstruction. In this example, the peak height from the ionosonde observations was estimated to be 275 km, so the peak height above Halley was underestimated by some 30 km (Fig. 4) in the tomographic plot when compared with that from the sounder. If a real difference in the peak height existed between Faraday and Halley then this would be undetected in the tomographic plot. Since the ionospheric sounders are separated by more than 10° in latitude and approximately 2.5 hours in local time, a difference in the peak height of 30 km would not be unreasonable. Furthermore, it should also be noted that peak heights estimated by the method used are only accurate to within approximately 15 km (Bradley & Dudeney 1973) and that in addition, the vertical pixel dimension in the tomographic reconstruction is 15 km. In the example shown here the tomographic technique overestimated the density at the F-layer peak above Halley by approximately 0.5 $x10^{11}m^{-3}$. This overestimation of the peak densities is partly because no E-layer or F1-layer was included in the initial estimate used for the background ionosphere so that the reconstruction method has incorrectly positioned this bottomside ionization at the F-layer peak.

To produce a more objective comparison for the entire period of the observations the peak densities from the tomographic reconstructions above Halley have been plotted against the peak densities determined from the dynasonde measurements (Fig. 5). It was not possible to compare all of the tomographic plots with corresponding dynasonde observations due to D-region absorption and strong sporadic E-layers reducing the availability of F-region echoes in the latter set. The overall agreement between the tomographic and dynasonde densities is good, with a linear regression yielding a slope of 1.11 ± 0.07. The slope is increased by the tendency of the tomographic technique to give a small over-estimate of the peak density due to the lack of E and F1-layer ionization, as in the example described earlier. This effect is most marked for tomographic peak densities between 5.0 x 10^{11} m^{-3} and 8.0 x 10^{11} m^{-3}, which correspond to satellite passes monitored during a permanently sunlit ionosphere, when the absence of an E-region in the tomographic plot will have a more pronounced influence on the derived peak density. At the highest peak densities, where the contribution from the E-layer is less significant, the two methods agree to within 7%.

A number of reconstructions show the mid-latitude trough which is often observed by the dynasonde to pass equatorwards over Halley in the midnight sector during the winter months (Dudeney *et al.* 1983). A typical example is shown in a tomographic plot for 18 June 1994 (Fig. 6). The satellite, travelling in a southward direction, crossed 70°S latitude at longitude 43.0°W at 01:56 UT. The main feature in the reconstruction is a deep ionization trough at 75.0°S, having a minimum peak density of about 0.3 x $10^{10}m^{-3}$. On the very steep poleward wall of the trough the peak densities increase by some 15 fold in 1° of latitude leading to a boundary blob centred on 76.5°S with a peak density in excess of 5.5 x 10^{10} m^{-3}. Equatorward of the trough the horizontal density increases much more slowly.

It is not possible to produce a vertical electron-density profile for this time from the dynasonde observations because there is an insufficient number of echoes from overhead. However, many F-region echoes were received from polewards of Halley. Using this spatial information, a gradient in the F-region electron density has been derived. The electron

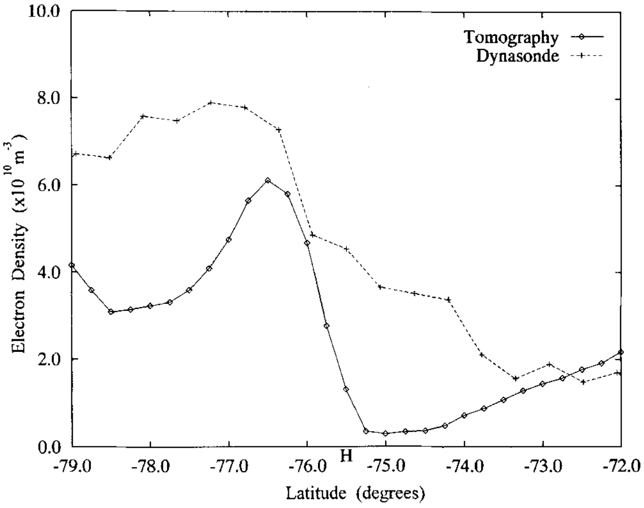

Fig. 7. Latitudinal gradients of the electron density at the F2-layer peak derived from the contour plot shown in Fig. 6 and from dynasonde measurements.

density is shown as a function of latitude in Fig. 7, along with the corresponding peak densities determined from the reconstruction. Both techniques show the same broad latitudinal features: an enhancement near 77.0°S, a steep poleward wall at 76.0°S and a region of depleted densities equatorward of 75.5°S. In general the electron densities are very low and the maximum difference in density found by the two techniques is only ~4 x 10^{10} m^{-3} across the latitudinal extent shown in the figure. The dynasonde technique is more sensitive to localized regions of higher density and therefore is less likely to receive echoes from the lowest ionization levels within the trough region, so the minimum seen is less deep than that found by the tomographic technique. In addition, the extreme geometry used in this experiment will produce tomographic plots biased towards the ionosphere west of Halley, where longitudinally structured features, such as the trough, may differ from overhead. Despite these factors, the overall agreement between the two sets of observations is good.

Conclusions

Results have been presented from the first basic ionospheric tomographic experiment in Antarctica. The reconstructed plots of electron density have been compared with observations made by the dynasonde ionospheric sounder located at Halley. In general, good agreement was found between the two techniques. Under quiet conditions, the bottomside ionization distributions overhead at Halley compared well, with the peak F2 densities agreeing to within about 10%. When horizontal structures were present within the vicinity of Halley the latitudinal density gradients showed the same gross features, though with some small discrepancy between densities. The results demonstrate the potential of the tomographic method to image large-scale ionospheric features even when restricted choice of ground-based receiving stations causes poor experimental geometry.

Work is now in progress to develop tomographic receivers to operate on Automated Geophysical Observatories (AGOs) deployed by BAS. The AGOs positioned along a geographic meridian polewards of Halley will provide a much improved geometry for tomography. The authenticity of the resultant reconstructed images of electron density is likely to be much improved.

Acknowledgements

We acknowledge gratefully the work of the British Antarctic Survey's field engineers in maintaining the ionospheric equipment at Halley and Faraday and record our thanks to Clive Willson and David Rice at Aberystwyth for their assistance with the project. The perceptive comments and the suggestions for improvement of the paper made by the referees are acknowledged with thanks.

References

Austen, J.R., Franke, S.J., Liu, C.H. & Yeh, K.C. 1986. Application of computerised tomography techniques to ionospheric research. *In* Tauriainen, A., *ed. Proceedings of International Beacon Satellite Symposium.* Oulu: University of Oulu, Finland, 25-35.

Bilitza, D. 1990. International reference ionosphere 1990. *National Space Science Data Center/World Data Center A for Rockets and Satellites,* 90-22.

Bradley, P.A. & Dudeney, J.R. 1973. A simple model of the vertical distribution of electron concentration in the ionosphere. *Journal of Atmospheric and Terrestrial Physics,* **35**, 2131-2146.

Broom, S.M. 1984. A new ionosonde for Argentine Islands ionospheric observatory, Faraday station. *British Antarctic Survey Bulletin,* No. 62, 1-6.

Dudeney, J.R., Jarvis, M.J., Kressman, R.I., Pinnock, M., Rodger, A.S. & Wright, K.H. 1982. Ionospheric troughs in Antarctica. *Nature,* **295**, 307-308.

Dudeney, J.R., Rodger, A.S. & Jarvis, M.J. 1983. Radio studies of the main F-region trough in Antarctica. *Radio Science,* **18**, 927-936.

Dudeney, J.R., Rodger, A.S., Smith, A.J., Jarvis, M.J. & Morrison, K. 1995. Satellite experiments simultaneous with Antarctic measurements (SESAME). *Space Science Reviews,* **71**, 705-742.

Heaton, J.A.T., Pryse, S.E. & Kersley, L. 1995. Improved background representation, ionosonde input, and independent verification in experimental ionospheric tomography. *Annales Geophysicae,* **13**, 1297-1303.

Kersley, L., Heaton, J.A.T., Pryse, S.E. & Raymund, T.D. 1993. Experimental ionospheric tomography with ionosonde input and EISCAT verification. *Annales Geophysicae,* **11**, 1064-1074.

Kersley, L. & Pryse, S.E. 1994. Development of experimental ionospheric tomography. *International Journal of Imaging Systems and Technology,* **5**, 141-147.

Leitinger, R., Schmidt, G. & Tauriainen, A. 1975. An evaluation method combining the differential doppler measurements from two stations that enables the calculation of the electron content of the ionosphere. *Journal of Geophysics,* **41**, 201-213.

PRYSE, S.E., MITCHELL, C.N., HEATON, J.A.T. & KERSLEY, L. 1995. Travelling ionospheric disturbances imaged by tomographic techniques. *Annales Geophysicae*, **13**, 1325-1331.

RAYMUND, T.D., AUSTEN, J.R., FRANKE, S.J., LIU, C.H., KLOBUCHAR, J.A. & STALKER, J. 1990. Application of computerised tomography to the investigation of ionospheric structures. *Radio Science*, **25**, 771-789.

RAYMUND, T.D. 1994. Ionospheric tomography algorithms. *International Journal of Imaging Systems and Technology*, **5**, 75-85.

TITHERIDGE, J.E. 1985. Ionogram analysis with the generalised program POLAN. *UAG Report, World Data Center A for Solar Terrestrial Physics, NOAA, Boulder, USA*.

https://doi.org/10.1017/S0954102096000430 Published online by Cambridge University Press