Ensemble Inversion Method for ISIS II Topside Ionograms

Donald D. Rice[1], Jan J. Sojka[1], J. Vincent Eccles[1], H. G. James[2], Charles Torre[3], R. F. Benson[4]

[1]Space Environment Corporation, PO Box 3985, Logan, UT, 84323, USA

[2]Natural Resources Canada Geomagnetic Laboratory,Ottawa, ON K1A 0E7, Canada

[3]Utah State University, Logan, UT, 84322, USA

[4]Geospace Physics Laboratory, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

ABSTRACT

The ISIS II topside sounding satellite was launched in 1971 and provided data until 1990. Topside data were recorded and archived on magnetic tape. A substantial portion of the data set was reproduced on 35mm film to enable manual analysis, but it is difficult to integrate film data with modern data analysis methods. Thus Space Environment Corporation (SEC) carried out a pilot project to convert films covering selected space weather events to digital form. Software has been developed to extract ionogram frames from the film and determine the virtual range and frequency scales. The geographic latitude, longitude, and altitude of the satellite is computed from the time stamps on the ionograms.

The ionogram inversion code originally developed by J. E. Jackson (*Proc. IEEE*, 57, 960, 1969) for the analysis of the topside datasets has been updated to run in the Linux environment. In addition, a new inversion code has been developed by C. Torre from first principles for comparison. The original code uses the ionogram X trace for its inversion; that trace is usually relatively well defined, but the inversion procedure is more complicated. The new method can use the X trace, but it can also use the O trace, which is often more difficult to identify clearly. Thus two independent analysis methods are available which can use two representations (O and X) of the topside ionogram.

Topside ionogram traces often have significant thickness in virtual range, particularly at high latitudes. Additionally, the presence of plasma resonance lines can make the determination of the critical frequencies at the satellite (f_xS and f_oS) imprecise. To quantify the uncertainties involved in specifying the traces, upper and lower bound traces are specified and inverted, providing a set of bounding electron density profiles (EDPs) for each trace and method. This set of six EDP estimates (two each from Jackson X, Torre O, and Torre X) can be further augmented by utilizing different analysis options in the Jackson code, and the estimates can be weighted according to the quality of the traces used for the inversion. The ensemble analysis of these EDP estimates provides a best estimate of the EDP including uncertainties.

This study presents several examples of ionogram inversions using the Jackson and Torre methods for different levels of geomagnetic activity at high latitudes. The practicality of converting and analyzing large quantities of the archived topside sounding film archives to online data collections is discussed.

1. INTRODUCTION

The International Satellites for Ionospheric Studies (ISIS) program devised in the 1960s was a joint effort of US and Canadian governments. It included the Alouette I and II and ISIS I and II satellites, which collected ionospheric topside sounding data from 1962-1990 [Benson, 2010]. The original topside ionograms were recorded on magnetic tape from the satellite telemetry, and a portion of the ionograms were also archived on 35mm film for analysis by researchers. Efforts have been made to convert some of the original telemetry tapes to online digital ionogram files [Benson and Bilitza, 2009], and a recent effort at Space Environment Corporation (SEC) has succeeded in converting a selection of the 35mm films to digital ionogram files [Rice et al., 2015; Eccles, 2015].

The current study is based on digitized film data from the ISIS II topside sounding satellite, launched in 1971 with a nearly-circular polar orbit at about 1400 km altitude. The focus is on high-latitude ionograms in the vicinity of Resolute Bay (74.7° N, -94.9° E) from disturbed periods in the early 1970s. Software has been developed to extract ionogram frames from the digitized film and to determine the virtual range and frequency scales. The ionogram grayscale is automatically adjusted with a histogram equalization procedure to provide consistent contrast. An ISIS utility is used to compute geographic latitude, longitude, and altitude of the satellite from the time stamps on the ionograms.

2. HIGH LATITUDE IONOGRAMS

Topside ionograms include many unique features compared to the more familiar bottomside ionograms, including plasma and electrostatic resonances, and variations of the Z trace [Hagg et al., 1969]. Additional features such as remote resonances and spread F are more common at high latitudes and during disturbances, which are the conditions chosen for this study.

An example of a high-latitude ISIS II ionogram (taken between 83.0° N, -68.7° E and 83.6° N, -67.3° E) is shown in Figure 1. The O, X, and Z traces are reasonably clear in this example, with well-defined f_oF_2 and f_xF_2 cusps. Faint reflections from the ground may be seen to the right of these cusps. Resonance spikes are visible at the gyrofrequency (f_h = 0.93 MHz, $2f_h$ = 1.86 MHz), plasma frequency (f_n = 1.07 MHz), and hybrid frequency (f_T = 1.4 MHz).

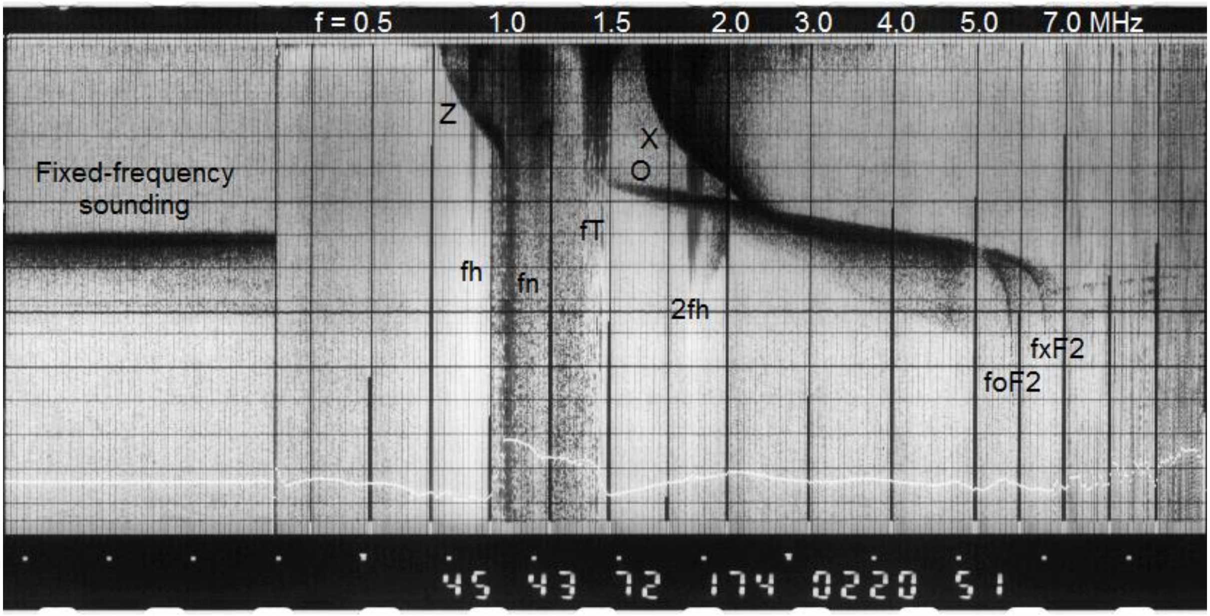


Figure 1. ISIS II high-latitude topside ionogram for 1972 day 174 at 02:20:51 UT.

The O and X traces in this figure exhibit spread-F typical of those seen in other high-latitude topside ionograms used in this study. The thickness of the traces makes it difficult to distinguish the O and X traces where the two overlap, and the determination of the critical frequencies at the satellite (f_xS and f_oS) can be imprecise.

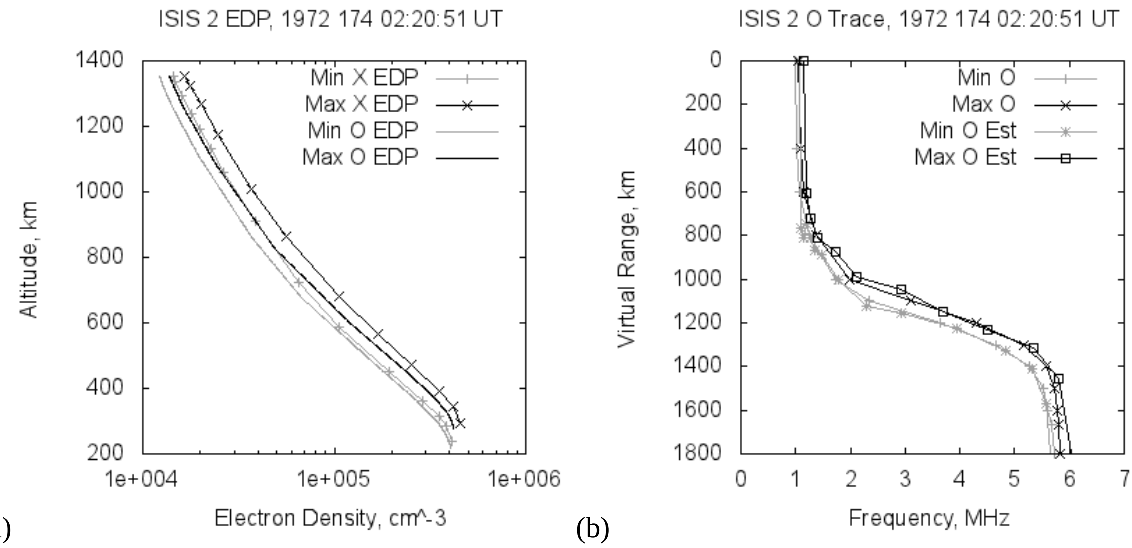
Hagg [1969] states that studies of spread-F in topside ionograms have shown that “the main X-wave trace occurs at just a few kilometers shorter range” than the maximum-range edge of the trace. However, where the separation of the O and X traces is unclear, identifying a likely trace remains uncertain.

To quantify the uncertainties involved in specifying the traces in these cases, plausible upper and lower bound traces are specified. Inverting these traces provides a set of bounding electron density profiles (EDPs). If both O and X traces are specified in this way, and different analyses are carried out using alternative assumptions, the resulting set of EDP estimates may be weighted according to the quality of the traces and likelihood of the assumptions. The ensemble analysis of these weighted EDP estimates then provides a best estimate of the EDP, including uncertainties.

3. TOPSIDE IONOGRAM INVERSION

A topside ionogram inversion code developed by Jackson [1969] has been the primary analysis tool for the ISIS datasets since it was created. The code inputs the X trace virtual range and frequency coordinates, geographical coordinates, and a gyrofrequency estimate. It generates an EDP and an estimated O trace. Jackson’s code has been updated to run in the modern Linux environment. The topside X trace is preferred for inversion because it is usually more complete; in Figure 1, the O trace is obscured by electrostatic interference between f_n and f_T.

A new inversion code has been developed by C. Torre from first principles that can use either the O or X trace along with model geomagnetic field data. The new method has been used primarily to compare EDPs based on the O trace with the Jackson X trace EDP, with good agreement. Figure 2(a) shows EDP from Jackson based on the X trace of Figure 1 with the EDP from Torre based on the hand-scaled O trace. The Torre EDP range closely follows the minimum Jackson EDP, which corresponds to the lower X trace in Figure 1. Thus the O trace inversion is consistent with Hagg’s assertion that the “main X trace” is near the bottom edge of the spread X trace.



(a) (b)

Figure 2. (a) Comparison of EDPs from Torre O trace and Jackson X trace analyses. (b) Comparison of O trace and O trace estimate from Jackson.

The hand-scaled O trace inputs to Torre's inversion are compared to the O traces estimated by Jackson's method from the X trace inputs in Figure 2(b). The two sets of traces are quite close despite the gap in the O trace seen in Figure 1.

A second example is shown in Figure 3, when ISIS II was between 74.0° N, -62.8° E and 74.5° N, -62.6° E. In this case, the plasma frequency is much lower (f_n = 0.65 MHz) with the gyrofrequency f_h = 0.92 MHz. Even though there is considerable spread, clear O and X traces can be seen within the spread F. The EDP derived from the O trace overlaps the lower range of the EDP derived from the X trace (Figure 4(a)). Comparing the hand-scaled O-trace to the O trace estimated by Jackson shows an instability or ringing effect in the Jackson O trace (Figure 4(b)). This behavior is found in many O traces estimated by Jackson, though the amplitude of the instability is usually much smaller.

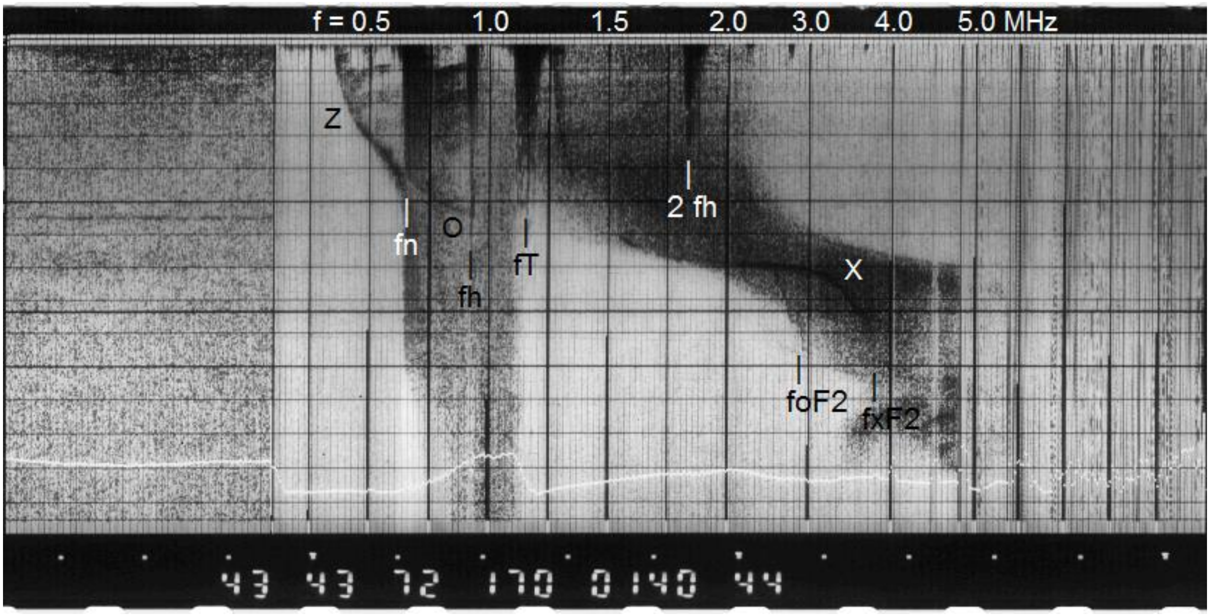
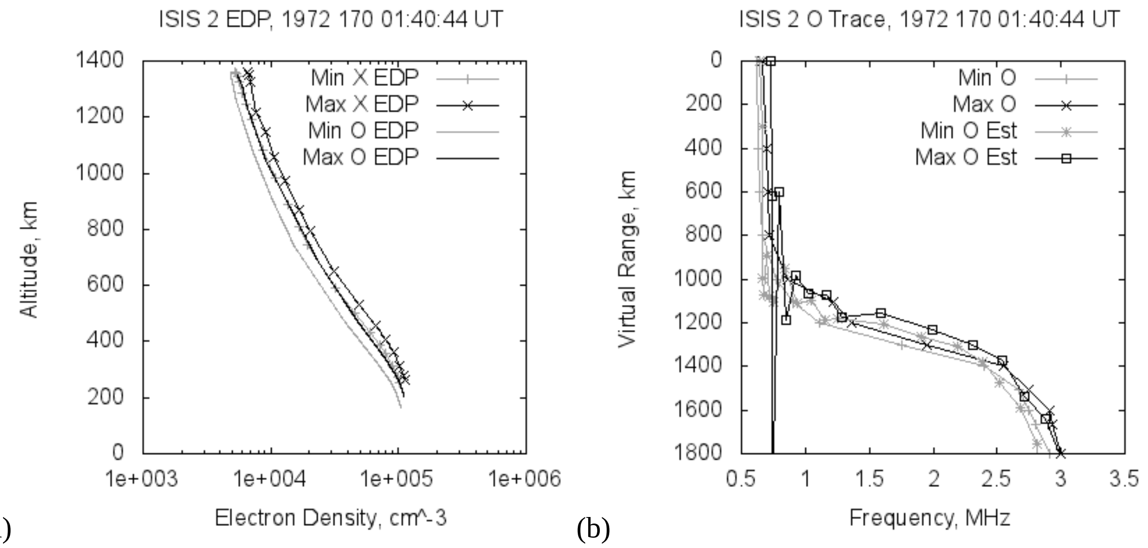


Figure 3. ISIS II high-latitude topside ionogram for 1972 day 170 at 01:40:44 UT.



(a) (b)

Figure 4. (a) Comparison of EDPs from Torre O trace and Jackson X trace analyses. (b) Comparison of O trace and O trace estimate from Jackson.

The Jackson code has a hard-coded limit of 50 trace points, and older examples of its use generally have 10-15 trace points, corresponding to about 2-3 trace points per MHz. A similar number of trace points has been used with the Torre code. A comparison run was made with 49 trace points for a trace that had small “wiggles”, but neither code showed a significant difference in the resulting EDPs versus using 15 trace points.

4. AN ENSEMBLE ELECTRON DENSITY PROFILE

For topside ionograms taken at high latitudes during disturbed space weather conditions, it is often difficult to unambiguously identify the “true trace” for either O or X. In these cases, it is reasonable to specify a lower and upper bound on each trace, with the expectation that the “true trace” may be found within the bounds. When the O and X traces are inverted by independent methods, two lower bounds and two upper bounds are produced for the EDP.

Further tests are planned using the X trace inversion with Torre’s code to see if any significant differences are found with the Jackson X trace inversion. The X trace inversion for both codes strongly depends on the value of the gyrofrequency, while the O trace inversion has only a weak dependence on the parameter. The gyrofrequency at the satellite height may be read directly from the resonance spike on the ionogram, but the variation with true height must be obtained from a magnetic field model. Thus, there may be differences between the Torre and Jackson X inversions due to differences in the gyrofrequency altitude variation function that each program uses.

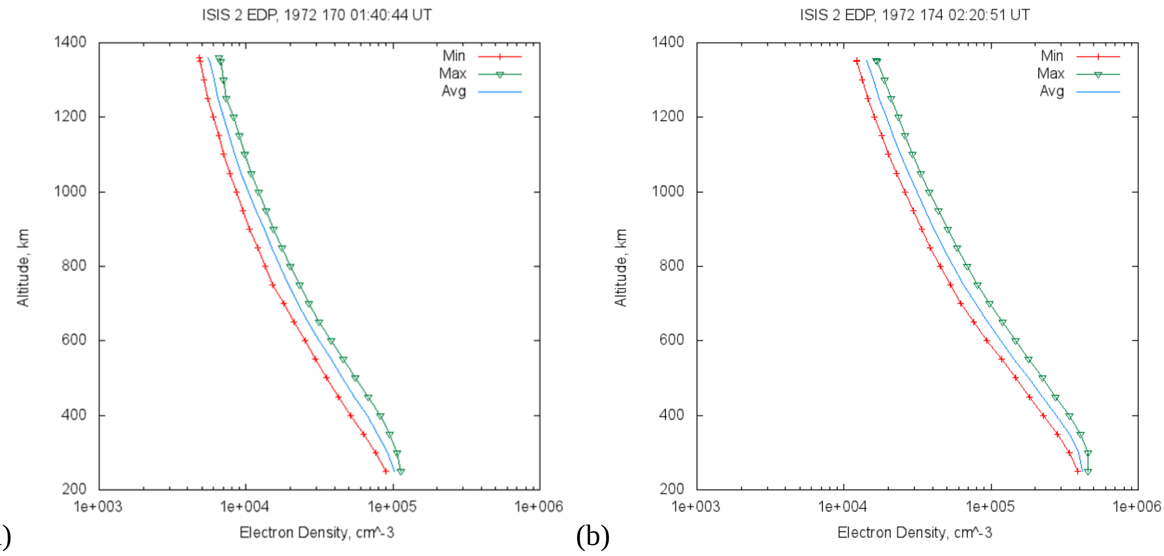
One factor that has not yet been evaluated is the change in magnetic field parameters due to the satellite’s orbital motion. The Jackson code has a provision for estimating this change, but it has not been explored. Inversions based on alternative assumptions about changing magnetic field parameters would add more EDP bounds to the set of results for a given ionogram.

Ultimately, a weighted average can be developed for the upper and lower EDP bound, with the weight assigned according to factors such as the quality of the input trace, the confidence in the inversion method, the change in the magnetic field during the sounding interval, and so on. The bounds would then be used to express the EDP as a best estimate plus or minus an uncertainty as illustrated in Figure 5. This method is used in SEC’s ESIR software for bottomside ionogram inversions, but more testing will be needed to implement it for the topside case.

5. CONCLUSIONS

The methods described above have been used to produce EDPs for more than 40 high-latitude storm-time ionograms from ISIS II. Problems and questions that have arisen during this analysis are still being addressed.

The ionogram virtual range and frequency scales can be identified automatically with reasonable accuracy, based on the grid lines recorded on the film ionograms. However, automatic identification of the traces and key resonance spikes does not appear to be practical at this time. A streamlined interactive manual identification procedure is being developed, and it is hoped that SEC’s current collection of digitized topside ionograms can be processed and added to the online topside archive, including consistent quality and uncertainty parameters.



(a) (b)

Figure 5. Ensemble average and bounds from the four EDPs shown in (a) the disturbed ionosphere of Figure 4(a); and in (b) the recovering ionosphere of Figure 2(a).

ACKNOWLEDGEMENTS

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