AGU100 ADVANCING EARTH AND SPACE SCIENCE

Radio Science

RESEARCH ARTICLE
10.1029/2018RS006659

Special Section:
URSI General Assembly and Scientific Symposium (2017)

Key Points:
- ISIS-1 digital topside ionogram database enhancements enable more efficient manual scaling and automatic processing
- Manual scaling indicates the need for improvements in existing automatic-processing software for ISIS-1 digital topside ionograms
- The new ISIS-1 ionograms are valuable for improving the International Reference Ionosphere model in the topside ionosphere

Correspondence to:
R. F. Benson,
robert.f.benson@nasa.gov

Citation:
Benson, R. F., Bilitza, D., Fung, S. F., Truhlik, V., & Wang, Y. (2018). Enhancing the ISIS-I topside digital ionogram database. *Radio Science*, *53*, 1492–1505. https://doi.org/10.1029/2018RS006659

Received 1 JUN 2018
Accepted 13 NOV 2018
Accepted article online 16 NOV 2018
Published online 15 DEC 2018

Enhancing the ISIS-I Topside Digital Ionogram Database

Robert F. Benson[1], Dieter Bilitza[2], Shing F. Fung[1], Vladimir Truhlik[3], and Yongli Wang[4]

[1]Geospace Physics Laboratory, Heliophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD, USA, [2]Heliospheric Physics Laboratory, Heliophysics Science Division, GMU/SWL/Goddard Space Flight Center, Greenbelt, MD, USA, [3]Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czech Republic, [4]Space Weather Laboratory, Heliophysics Science Division, UMBC/GPHI/Goddard Space Flight Center, Greenbelt, MD, USA

Abstract Selected original analog telemetry tapes from three of the topside-sounder satellites of the International Satellites for Ionospheric Studies (ISIS) program, namely Alouette 2, ISIS I, and ISIS II, were used in an earlier project to produce more than ½ million digital topside ionograms; the resulting digital topside ionograms from ISIS II were used to produce more than 86,000 globally distributed vertical topside ionospheric electron density profiles $N_e(h)$ that cover a time span of more than a solar cycle. These $N_e(h)$ were produced using the Topside Ionogram Scaler with True height algorithm auto-scaling software. Before attempting to automatically process Alouette-2 or ISIS-I ionograms, a data-enhancement project was initiated so as to increase the number of ionograms suitable for manual scaling and to increase the auto-processing success rate. These enhancements were mainly to correct problems that often occurred during the analog-to-digital conversion of the original telemetry tapes. Here we illustrate the improvements made to the ISIS-I digital topside ionograms and compare N_e values at the satellite altitude and $N_e(h)$ profiles, based on the manual scaling of selected ionograms, to both the auto-scaled values and the predictions of the International Reference Ionosphere 2016 model. The results indicate the need to improve the available auto-processing software for the new ISIS-I digital ionograms and that International Reference Ionosphere 2016 predicts midlatitude winter topside N_e values that are too high in the late morning and at noon but too low in the early morning.

Plain Language Summary Data from the Alouette/ISIS topside-sounder satellites from the 1960s and 1970s still provide some of the most useful information on the topside ionosphere on a global scale. This region, that is, above the electron density peak near 300-km altitude, is not very well represented by ionospheric models, yet it has a significant impact on advanced technological systems, such as navigation, that depend on radio signals that traverse the entire ionosphere. This study builds on earlier investigations and uses the latest digital files from the International Satellites for Ionospheric Studies-I satellite to demonstrate the importance of these files, the challenges encountered in developing software to automatically process them, and to indicate regions where the International Reference Ionosphere model is in need of improvement.

1. Introduction

The four polar-orbiting Canadian-built and U.S. launched topside-sounder satellites Alouette 1 (circular 80° inclination orbit at 1,000 km), Alouette 2 (elliptical 80° from 500 to 3,000 km), International Satellites for Ionospheric Studies (ISIS) I (elliptical 88° from 565 to 3,500 km), and ISIS II (circular 89° at 1,400 km) were included in the six-satellite ISIS program; the other two were the U.S. Explorer 20 (launched into an orbit similar to Alouette 1 and performed fixed-frequency ionospheric soundings) and Explorer 31 (same orbit as Alouette 2) satellites (Jackson, 1986; Jackson & Warren, 1969). The latter satellite was also known as Direct Measurements Explorer A and was launched together with Alouette 2. The four Alouette/ISIS satellites were launched between 1962 and 1971, and each operated for 10 or more years to produce 60 satellite years of swept-frequency ionospheric topside sounder observations. These sounders were designed as analog systems, and the data were recorded on analog seven-track telemetry tapes at a globally distributed network of telemetry stations as illustrated in Figure 2 of Benson and Bilitza (2009). Cost considerations prevented all of the sounder data from being converted to 35-mm film topside ionograms. An Analog-to-Digital (A/D) conversion project was conducted at the NASA/Goddard Space Flight Center to process some 16,000 of the original telemetry tapes from Alouette 2, ISIS I, and ISIS II; more than 588,000 digital topside ionograms were produced (Benson, 1996; Benson & Bilitza, 2009). The ISIS-II digital topside ionograms were automatically processed to produce more than 86,000 globally distributed vertical topside ionospheric electron density profiles $N_e(h)$ using the Topside Ionogram Scaler with True height algorithm (TOPIST; Bilitza et al., 2004; Huang et al., 2002). Some files that were auto-processed, however, yielded erroneous topside $N_e(h)$ due to incorrect starting conditions for the ionospheric reflection traces; this situation motivated changes to the scheme for identifying sounder-stimulated plasma resonances and wave cutoffs in the TOPIST software for the auto-processing of ISIS-II topside digital ionograms (Benson et al., 2012). Still, many of the ISIS-II digital ionograms could not be auto-processed due to problems encountered during the A/D operation; the main problem occurred when an ionogram frame-sync pulse could not be properly detected. A data-enhancement project was initiated to overcome this limitation for the processing of topside digital ionograms from the Alouette-2 and ISIS-I topside sounders (Benson et al., 2012; Wang et al., 2015). First priority was given to the enhancement of the ISIS-I data because of the large number of digital ionograms available, the data time span from 1969 to 1983, and because of the similar ionogram format to that of ISIS II (a few seconds of fixed-frequency operation followed by swept-frequency operation to 10 or 20 MHz). ISIS I is a valuable complement to ISIS II because it includes altitudes up to 3,500 km (well above the 1,400-km limit for ISIS II) where predictions based on the International Reference Ionosphere 2016 (IRI-2016) model (Bilitza et al., 2017) are in great need of improvement. While Benson et al. (2012) demonstrated the approach of this data-enhancement project on some problem ISIS-I digital topside ionograms, the purpose of the present paper is to (1) present the results of applying TOPIST auto-processing software (originally developed for ISIS-II) to produce thousands of topside electron-density profiles from enhanced ISIS-I digital ionogram files recorded at one midlatitude telemetry station (Ottawa) over a time interval spanning more than a solar cycle, (2) check these auto-processed files by comparing the results with manual scaling of selected ionograms, and (3) compare IRI-2016 predictions, using the NeQuick option, to the auto-scaled and manual-scaled results.

2. TOPIST-Processed ISIS-II Topside $N_e(h)$

Most topside $N_e(h)$ available after 1969 are from ISIS II. They are either from the hand scaling of 35-mm film ionograms or from the auto TOPIST-processing of digital ionograms but most are from the latter (see Figure 1 a). Only slightly more than one third of the available ISIS-II topside digital ionograms (see Figure 1b) were capable of being auto-processed by TOPIST, and not all of the output files produced $N_e(h)$ profiles. (The label in Figure 1a is not correct in the case of ISIS 2/TOPIST since these values in the histogram correspond to the number of available TOPIST files rather than the number of profiles.) Many of the ISIS-II digital ionograms did not yield $N_e(h)$ because some of the sounding modes were either passive or fixed-frequency operation. In the former, the sounder transmitter is off, but the receiver is sweeping in frequency; in the latter, the sounder transmitter and receiver are held at a selected frequency. While ionograms resulting from these conditions are useful for investigating N_e gradients along the satellite orbit, auroral kilometric radiation and other natural emissions, sounder-stimulated plasma resonances, and so forth, they will not contain swept-frequency ionospheric reflection traces to invert into $N_e(h)$. In addition, some of the ISIS-II ionograms with reflection traces could not be auto-processed by TOPIST due to (1) incomplete reflection traces, (2) the presence of strong field-aligned reflection traces, spread F, or interference, (3) incorrect starting conditions due to the misidentification of wave cutoffs and sounder-stimulated plasma resonances, or (4) problems with the digital files due to difficulties encountered during the A/D processing of the analog telemetry tapes (and similar to those discussed in connection with the ISIS-I digital ionogram files in section 3).

TOPIST could not process many of the ISIS-II digital ionogram files, and it was often not clear why the processing failed. There were four possible outcomes for those that were processed: (1) the file could be processed, but the reflection trace data were not sufficient to produce a $N_e(h)$, (2) a $N_e(h)$ could be produced, but it was of the lowest quality ($q = 1$) due to severe spread F or the reflection traces calculated from the derived $N_e(h)$ did not agree very well with the auto-scaled traces, (3) the $N_e(h)$ was considered to be of medium quality ($q = 2$) because, even though the conditions for $q = 1$ were not present, the deduced height of the F peak hmF2 differed from the IRI model value by more than 50 km or the foF2 value was considered to be greater than the auto-scaled high-frequency cusp of the reflection trace, or (4) the $N_e(h)$ was considered to be of the highest quality ($q = 3$) because neither the conditions for $q = 1$ or $q = 2$ were present. These quality codes were incorporated into the TOPIST software developed by Huang et al. (2002). In view of more recent work, indicating that IRI hmF2 predictions can differ from observations by more than 50 km depending on season

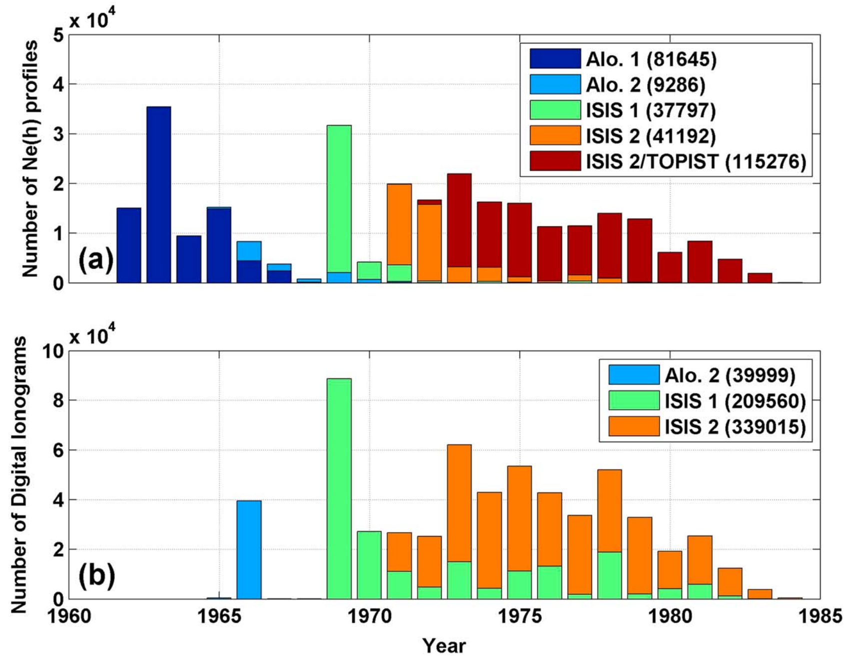

Figure 1. Data sets available from the NASA Space Physics Data Facility at http://spdf.gsfc.nasa.gov/isis/isis-status.html as of January 2009: (a) manually scaled topside N_e(h) from Alouette-1, Alouette-2, ISIS-I, and ISIS-II 35-mm film topside ionograms and the number of digital files resulting from the processing of all ISIS-II digital ionograms using TOPIST and (b) digital topside ionograms from Alouette 2, ISIS I, and ISIS II selected to obtain global coverage and to complement the earlier manually scaled data (note the factor of 2 change in scale relative to a). (Figure after Benson & Bilitza, 2009.) ISIS = International Satellites for Ionospheric Studies; TOPIST = Topside Ionogram Scaler with True height algorithm.

and time of day both in high (Themens et al., 2014) and mid-to-low (Sethi et al., 2008) latitudes, the quality codes may not be as valuable as originally intended. While q = 1 is likely to indicate the presence of spread F, comparisons between the TOPIST-derived and IRI-predicted hmF2 and foF2 values could lead to a good TOPIST profile being downgraded to q = 2 and a bad TOPIST profile being rated as q = 3.

The question then is how to distinguish between bad and good TOPIST profiles. Benson and Bilitza (2009) addressed this problem by comparing the N_e(h) profiles resulting from scaling ISIS-II topside digital ionograms using two different methods. One was based on TOPIST auto-processing, and the other was based on manual scaling of the ionospheric reflection traces and using the true-height inversion program developed by Jackson (1969a). The accuracy of the latter has been investigated in detail in several studies: Jackson (1969b) found the Alouette 1 and 2 topside N_e(h) profiles to provide accurate altitudes to within about 20 km near the F-region peak N_e based on comparisons with rocket, incoherent scatter, and ground-based ionosonde measurements; Whitteker et al. (1976) compared topside Alouette-2 and ISIS-I N_e(h) and also ISIS-I and ISIS-II N_e(h) during polar-cap conjunctions between the satellites and found good agreement among the remote measurements (within 10%); and Hoegy and Benson (1988) found agreement between ISIS-I and ISIS-II N_e(h) profiles and Dynamics Explorer 2 Langmuir-probe N_e measurements near the F-region peak to be within about 30% over a density range of more that two decades on three of four magnetic field-aligned conjunctions between the ISIS satellites and Dynamics Explorer 2; the agreement on the fourth conjunction, which had less available data and occurred in a region of strong Ne irregularities, was about 60%.

Benson and Bilitza (2009) used two ISIS-II ionograms for their comparisons between TOPIST auto-scaling and manual scaling based on Jackson's inversion routine; one from low latitudes and one from high latitudes. The corresponding IRI profiles were also presented to see how well the model predictions compared with actual observations. The low-latitude comparisons were very good except that the TOPIST profile extrapolated to a lower hmF2 value. The corresponding IRI profile was observed to be about 24% below the TOPIST profile. In the high-latitude comparison, the manual and TOPIST profiles agreed near the F-region peak but increasingly differed, as the altitude increased, to a 14% difference (TOPIST with higher N_e values) at the 1,400-km satellite

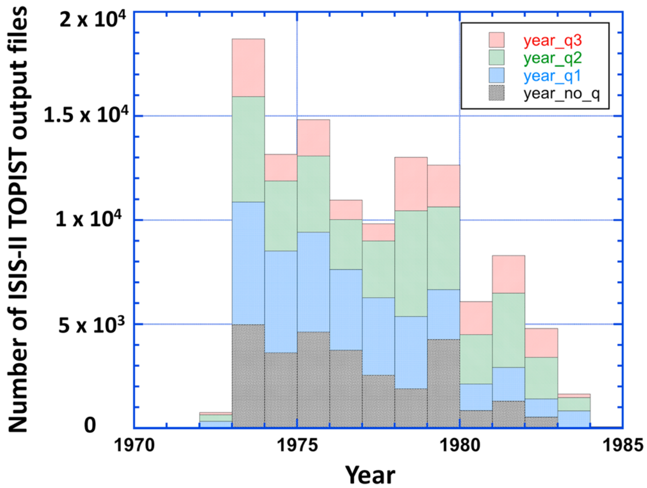

Figure 2. Number of ISIS-II TOPIST N_e(h), broken down by quality codes: q = 3 (highest quality; upper red-shaded areas), q = 2 (medium quality; next-lower green-shaded areas), q = 1 (lowest quality; next-lower blue-shaded areas), or "no q" (or a q value but defective data so that no N_e(h) was produced; the lowest black-shaded areas). ISIS = International Satellites for Ionospheric Studies; TOPIST = Topside Ionogram Scaler with True height algorithm.

altitude. This difference at the satellite altitude was attributed to a significant N_e gradient along the satellite path that affected the TOPIST interpretation of the detected resonance and wave cutoff frequencies (TOPIST assumes that gradients due to satellite motion can be neglected during the analysis of an ionogram). The corresponding IRI profile, while agreeing with the TOPIST and manually scaled profiles near the F peak, had N_e values about 67% below the TOPIST values at the satellite altitude. This increasing problem with the IRI model at high altitudes emphasizes the value of ISIS I with the capability of providing global N_e values, well above the 1,400-km limit of ISIS II, to improve IRI predictions.

Benson et al. (2012) checked the accuracy of the auto-processed TOPIST ISIS-II topside N_e(h) with hand-scaled profiles produced in the 1960s (using Jackson's program) and available from the NASA Space Physics Data Facility (SPDF). They found 248 topside ionograms that were processed both ways, and 42 of the possible comparisons had high quality codes (q = 3 for TOPIST) for each technique. Comparisons of these high-quality cases indicated that 55% of the comparisons had differences in N_e at the satellite altitude of 1,400 km of less than 10%, more than 85% had differences less than 20%, and less than 2.5% had differences greater than a factor of 2. In addition, three of the comparisons were checked by manually scaling the plasma resonances and wave cutoffs from the corresponding digital ionograms for an additional check of the N_e values at the satellite altitude. In each case (one where the TOPIST and hand-scaled profiles agreed and two where they did not), the manual scaling confirmed that the starting values of the hand-scaled profiles were correct. The TOPIST plasma resonance and wave cutoff routine was improved based on these comparisons. This improved version of TOPIST was used to automatically process the ISIS-I digital topside ionograms used in the present work.

The distributions of the four possible outcomes of TOPIST processing of the ISIS-II digital ionogram data are presented in Figure 2. There are 86,545 ISIS-II TOPIST N_e(h) (17,278 q = 3; 35,201 q = 2; 34,066 q = 1) and 28,725 ISIS-II TOPIST no-q files (including 225 with defective data), that is, without N_e(h) profiles, for a total of 115,270 (the total given in Figure 1a included six TOPIST files with zero size). The totals indicate that when TOPIST could automatically process ISIS-II ionograms to produce N_e(h) that about 60% were either of medium or high quality, that is, with q = 2 or 3.

The large ISIS-II digital topside ionogram database, indicated in Figure 1b, has enabled a variety of scientific investigations. For example, efficient search procedures were used to identify fixed-frequency ionograms recorded during specific geomagnetic conditions to support a theoretical interpretation of a sounder-stimulated plasma resonance that has remained a mystery for decades, that is, the resonance at the electron gyrofrequency (Muldrew, 2006); the large ISIS-II digital topside ionogram database, and the large topside N_e(h) database indicated in Figure 1a, enabled changes in high-latitude N_e(h) stimulated by large magnetic storms to be compared with changes in solar-wind parameters (Benson et al., 2016); and the large TOPIST N_e(h) database was used, together with higher-altitude N_e field-aligned profiles obtained by the Radio Plasma Imager on the IMAGE satellite, to improve the empirical IRI model in the topside ionosphere and to extend it into the plasmasphere (Reinisch et al., 2007).

3. Version-2 ISIS-I Digital Topside Ionograms

Version-2 ISIS-I topside digital ionograms have been produced and are available from the NASA/SPDF, from the midlatitude (45°N, 284°E) Ottawa (OTT) telemetry station (80,496 files from 1969 to1983 are available; Wang et al., 2015), the low-latitude (−1°S, 281°E) Quito (18,846 files from 1969 to 1972 are available telemetry station), and the high-latitude (65°N, 212°E) University of Alaska (3,211 files from 1975, 1978, and 1979 are available) telemetry station. These files are available from ftp://cdaweb.gsfc.nasa.gov/pub/data/isis/topside_sounder/ionogram_new_i1_cdf/isis1/. Currently, we are processing files from the midlatitude (33°S, 289°E) Santiago telemetry station. A major goal is to produce as many topside ionospheric N_e(h) as

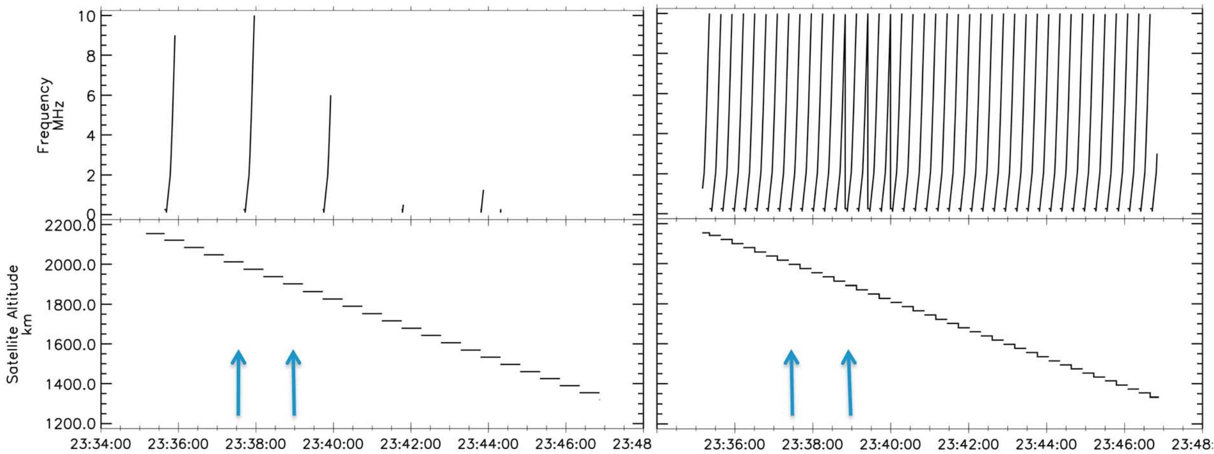

Figure 3. Comparing available frequency information (0.1 to 10 MHz in the top panels) and file start times (each at a different altitude in the range from 1,200 to 2,200 km in the bottom panels) for *av* (left panels) and *av2* (right panels) for Ottawa International Satellites for Ionospheric Studies-I data from 2334 to 2348 UT on 25 January 1976. The 1.5-min portions between the arrows are presented in Figure 4 with the addition of sounder data.

possible so as to expand the $N_e(h)$ profile coverage in latitude, longitude, and epoch available from the NASA/SPDF. Figures 3–5 were generated using the public data-display service of the NASA/SPDF CDAWeb system (available from http://spdf.gsfc.nasa.gov/isis/isis-status.html), to illustrate some of the differences between the original (version-1) files, designated as *av* for average files where the apparent-range information was averaged to yield 15-km resolution, and the enhanced files designated as *av2*. Both have good ionogram data, but the lack of proper frame-sync detection in the *av* files often prevented the determination of frequency information. This lack of proper frame-sync detection is apparent by

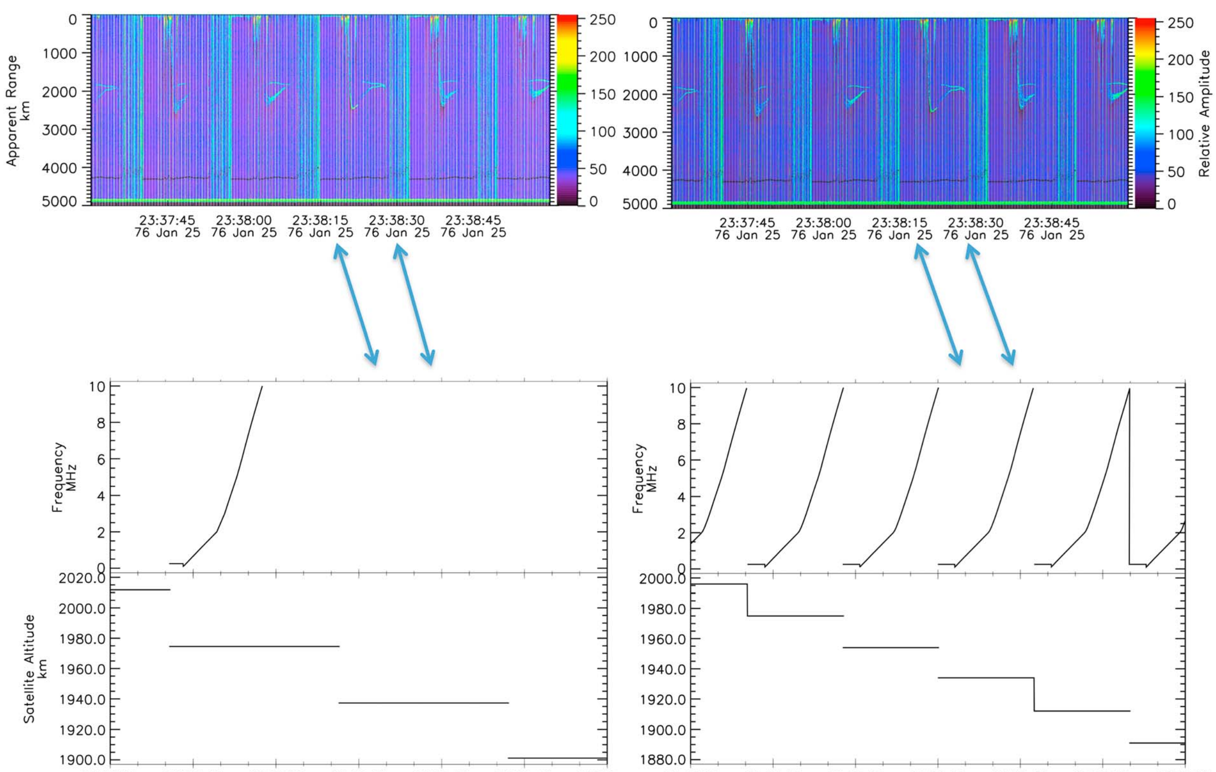

Figure 4. Same as Figure 3 except for only the Ottawa International Satellites for Ionospheric Studies-I data from 2337:30 to 2339:00 UT on 25 January 1976, the altitude scales are different, and the sounder data appear in the top panels. The 10-s portions between the arrows are expanded in Figure 5.

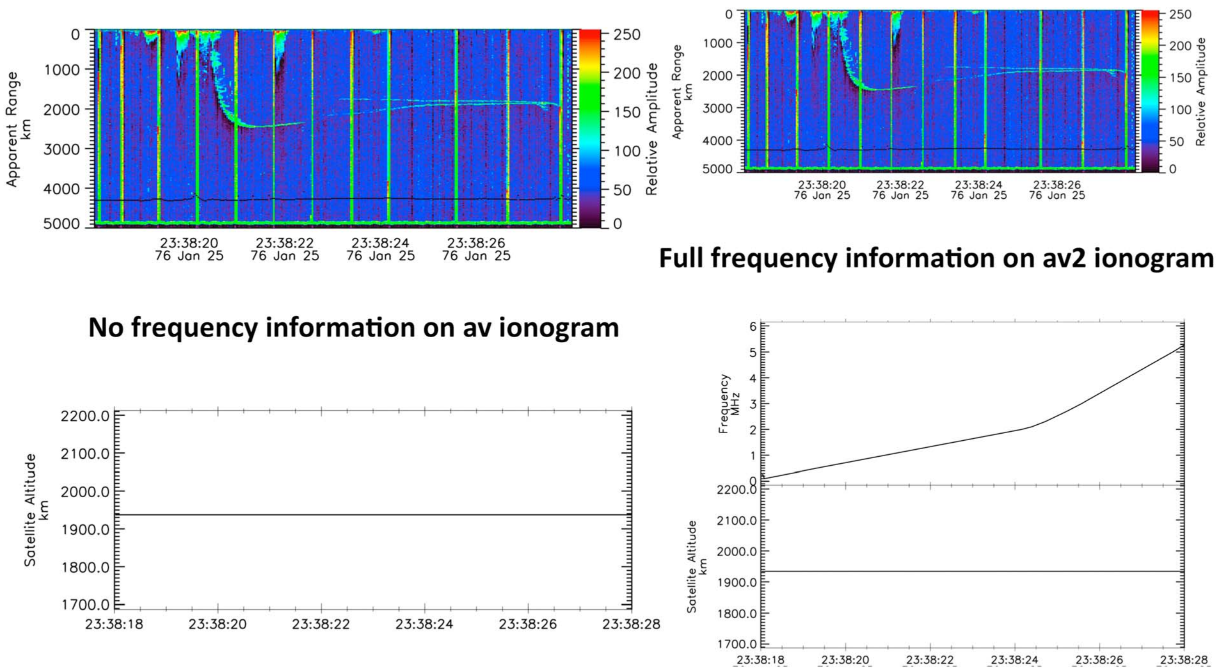

Figure 5. Same as Figure 4 except for only the 10-s intervals of swept-frequency operation from 0.1 to 5 MHz during the Ottawa International Satellites for Ionospheric Studies-I *av* (left) and *av2* (right) ionograms from 2338:18 to 2338:28 UT on 25 January 1976. The altitude is the value at the start of the file.

comparing the number of *av* and *av2* altitude steps in Figures 3 and 4. Each altitude step corresponds to the satellite altitude at the time of ionogram frame sync-pulse detection during the A/D operation. After correcting the frame-sync detection, it is possible to add the correct frequency information, as indicated in the right panels of Figures 3–5, allowing the ionograms to be processed automatically, by software such as TOPIST, to yield topside N_e(h).

4. Results Using Version-2 ISIS-I Ionograms

The auto-processing of version-2 ISIS-I digital topside ionogram files using TOPIST is not completely automatic as about 5% of the files cause the software to stop. When the program stops, the offending file is removed from the data set, and processing is resumed. More than 17,000 TOPIST files have been produced from the processing of version-2 ISIS-I OTT files from 1969 to 1983. They are available from https://spdf.gsfc.nasa.gov/pub/data/isis/topside_sounder/topist_ne_profile_ascii/OTT_45N_284E/. Not all of these files contain N_e(h) profiles. There were a small number (327) that contained bad data, for example, **** appeared in place of real values. There were many (8,245) that contained no profile information, so no quality flag (q value) was given. Such a large number (almost half of the output files after excluding the bad data files) is not surprising considering that ISIS I often operated in the D mode (two ionograms with the sounder "on" followed by two ionograms with the sounder transmitter "off" but the sounder receiver "on"), so it was only possible to have one half of a D-mode pass produce profiles. Also, sometimes an entire pass would be either in a passive-only mode or operating at a fixed frequency where it would not be possible to get profiles. But 8,782 of the TOPIST files produced topside N_e(h) profiles (5,281 automatically flagged by the TOPIST software as being of the lowest quality, that is, with q = 1; 3,189 with q = 2; and 312 with q = 3). Plotting about 200 of these profiles and comparing each with those obtained from IRI-2016 to have some point of comparison, it became clear that the TOPIST ISIS-I quality flags are not always reliable (most likely for the reasons stated in section 2 pertaining to the ISIS-II TOPIST results). Sample comparisons are given in Figures 6 and 7, for each q value, when the agreement in the topside ionosphere is good (within about 10%) and not good, respectively. While the IRI-2016 profiles provide a helpful comparison, the most reliable way to determine if a particular TOPIST profile is correct is to inspect the original ionogram. The inspection procedure is illustrated for the two TOPIST highest quality N_e(h) profiles (q = 3) of Figures 6 and 7 in Figures 8 and 9, respectively.

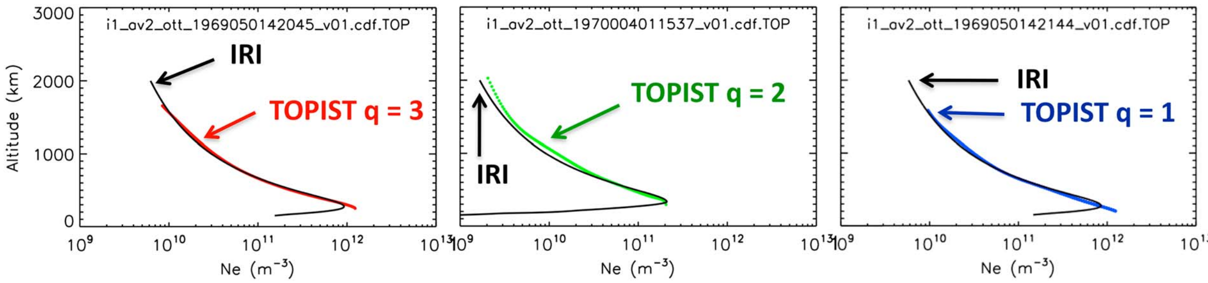

Figure 6. TOPIST N_e(h) examples with q = 3 (left), 2 (middle), and 1 (right) with good topside agreement with the IRI-2016. IRI = International Reference Ionosphere; TOPIST = Topside Ionogram Scaler with True height algorithm.

Note in Figure 8 that the TOPIST software correctly identified the electron gyrofrequency (H), the electron plasma frequency (N), and the cutoff of the extraordinary trace at the satellite (X). This is not the case for Figure 9 that presents the ionogram corresponding to the left panel of Figure 7 where there are major differences between the TOPIST q = 3 and the IRI-2016 N_e(h) profiles. In this case TOPIST identified H fairly accurately, but it erroneously identified N, corresponding to the start of the ordinary-mode trace (O) at the satellite, as being at the low-frequency side of 2H rather than its correct value near H as indicated by the manually scaled values given in black type above the ionogram. This large error in auto-determination of the electron plasma frequency at the satellite altitude led to the large excess of the electron density (relative to the IRI-2016 profile) at the start of the TOPIST auto-scaled profile in the left panel of Figure 7.

The TOPIST software also contains a manual-scaling option. Using that option, and scaling the proper X trace on the ionogram of Figure 9, leads to the results shown in Figure 10. This figure is a repeat of the left panel of Figure 7 with the addition of the N_e(h) profile based on the TOPIST profile based on using the manual-scaling option. This manually scaled TOPIST N_e(h) profile is considerably different than the auto-scaled TOPIST profile, and it indicates that the IRI-2016 profile predicts a N_e value at the satellite altitude of 2,000 km that is too high rather than too low.

Three of the profiles of Figures 6 and 7 are from ionograms from the same OTT ISIS-I satellite pass on day 50 (19 February) of 1969. TOPIST N_e(h) profiles from 12 of these ionograms, including the above three, are presented in the left panel of Figure 11. The profiles are numbered according to increasing ionogram start times as given in Table 1. Twelve distinct curves are not apparent since many of the profiles overlap over most of their altitude range. There are eight red profiles (where the TOPIST auto-processing gave the highest rating of q = 3), three green profiles (corresponding to a TOPIST rating of q = 2), and one blue curve (corresponding to the lowest TOPIST rating of q = 1); see Table 1 for the identification of these profiles by profile number.

Three approaches were used in an attempt to determine which of the profiles in the left panel of Figure 11 were correct. First, the plasma resonances on all of the ionograms leading to these profiles were scaled, as in Figures 8 and 9, to determine the electron density at the satellite $[(N_e)_{sat}]_{res}$, and these measured values were then compared to the TOPIST-determined values $[(N_e)_{sat}]_{topist}$ (corresponding to the top of each TOPIST profile in the left panel of Figure 11). The five TOPIST profiles on the right of the figure (represented by the two

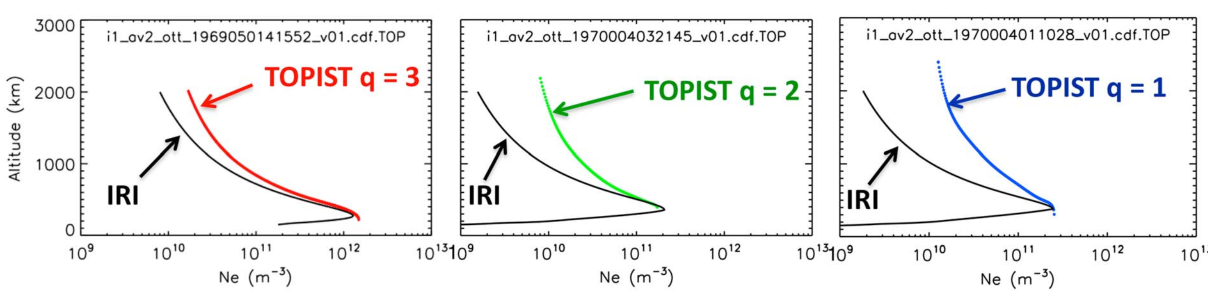

Figure 7. Same as Figure 6 except for TOPIST N_e(h) examples where the agreement with IRI-2016 in the topside ionosphere is not good. IRI = International Reference Ionosphere; TOPIST = Topside Ionogram Scaler with True height algorithm.

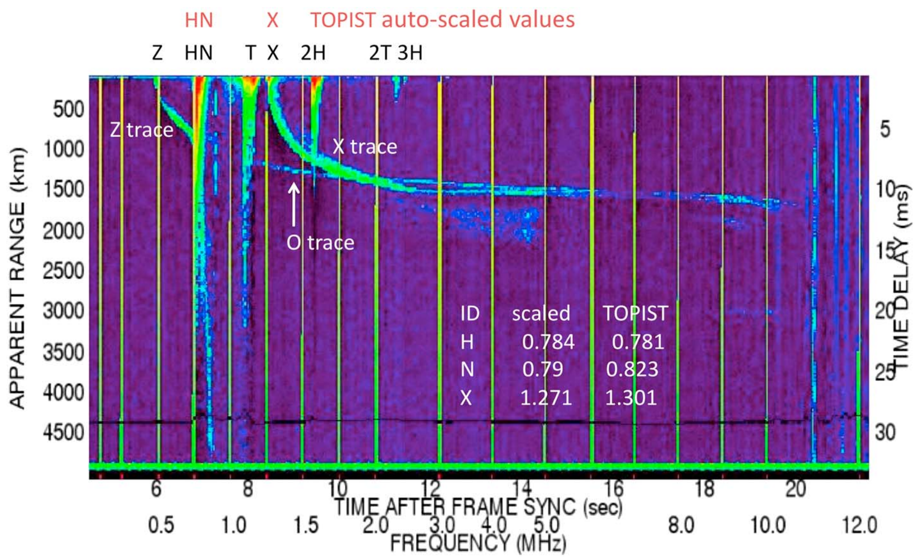

Figure 8. Part of the swept-frequency portion of the International Satellites for Ionospheric Studies-1 digital topside ionogram used to obtain the $N_e(h)$ profiles in the left panel of Figure 6, that is, corresponding to the situation where the TOPIST highest quality (q = 3) profile and the International Reference Ionosphere 2016 profile agree. The vertical scales on the right and left give the time delay after each sounder pulse of 0.1-ms duration and the apparent range derived from the time delay assuming free-space propagation, respectively. The two scales at the bottom provide the times after the ionogram frame-sync pulse (upper scale) and the corresponding sounder frequency (lower scale). The manually scaled values for the wave propagation cutoff frequencies and the frequencies of sounder-stimulated plasma resonances are indicated by the black letters at the top of the ionogram (Z and X for the two branches of the extraordinary wave; H, 2H, and 3H for the resonances at the electron gyrofrequency and its harmonics; N for the electron plasma frequency; and T and 2T for the upper-hybrid frequency and its harmonic). Red letters above the black letters indicates the TOPIST auto-scaled values for some of these features. The actual scaled and TOPIST values for the H, N, and X features are given within the ionogram. (Ottawa International Satellites for Ionospheric Studies-I ionogram at 1969_050_1420:45 UT, 1,657-km HGT, 0919 GMLTM, 57.6° GMLAT, −6.3° GMLONG, 62.0 INVLAT.) TOPIST = Topside Ionogram Scaler with True height algorithm.

red curves and the green curve) all had $[(N_e)_{sat}]_{topist}$ values way above the $[(N_e)_{sat}]_{res}$ values, that is, by more than a factor of 2 (profiles 2 and 3), by more than a factor of 3 (profiles 1 and 5), and by more than a factor of 8 (profile 8). The seven TOPIST profiles on the left (4, 6, 7, and 9–12) had $[(N_e)_{sat}]_{topist}$ values within 20% of the $[(N_e)_{sat}]_{res}$ values. The TOPIST and plasma resonance $(N_e)_{sat}$ values and their percentage differences are presented in Table 1. The largest difference is seen for profile 8. In this case the TOPIST auto-processing erroneously identified the plasma resonance at 3H as N. Recall that in the ISIS-I ionogram shown in Figure 9 that the TOPIST auto-processing erroneously placed N near 2H leading to the incorrect topside $N_e(h)$ profile in the left panel of Figure 7 (and corresponding to profile 1 in the left panel of Figure 11). The profiles from the left panel of Figure 11 are presented in the right panel of Figure 11 with the superposition of the predicted IRI-2016 profiles corresponding to each of the TOPIST profiles. The IRI-2016 predicted values $[(N_e)_{sat}]_{iri}$, corresponding to the top of each TOPIST profile, were determined and compared with the $[(N_e)_{sat}]_{res}$ values used to check the TOPIST auto-scaling. The $[(N_e)_{sat}]_{iri}$ values and their percentage differences relative to the $[(N_e)_{sat}]_{res}$ values are presented in Table 1. The IRI-2016 predictions are found to be too high by about 60% during the early times in this midlatitude late morning winter satellite pass, when ISIS-I was near 2,000-km altitude, but within about 30% during later times, as ISIS-I approached 1,600 km.

The second approach to investigate the profiles in the left panel of Figure 11 was to check the TOPIST auto-scaled $(N_e)_{max}$ values near 200-km altitude by comparing them to hourly values of the Ottawa ground-based ionosonde. The ISIS-I satellite was closest to this ionosonde location (45°N. Lat., 284°E. Long.) between the recording of profiles 10 and 11 (at 1420:16 and 1420:45 UT on 19 February 1969 between 44.5° and 46.0°N. Lat. at 286°E. Long.). As indicated in Table 1, the $[(N_e)_{sat}]_{topist}$ values agree within 10% of the $[(N_e)_{sat}]_{res}$ values for profiles 10 and 11; the $(N_e)_{max}$ values near 200-km altitude for these profiles were 1.3 and 1.2×10^{12} m^{-3}, respectively. These values agree favorably with the hourly ionosonde values of 1.1 and 1.3×10^{12} m^{-3} at 1400 and 1500 UT on this day, respectively.

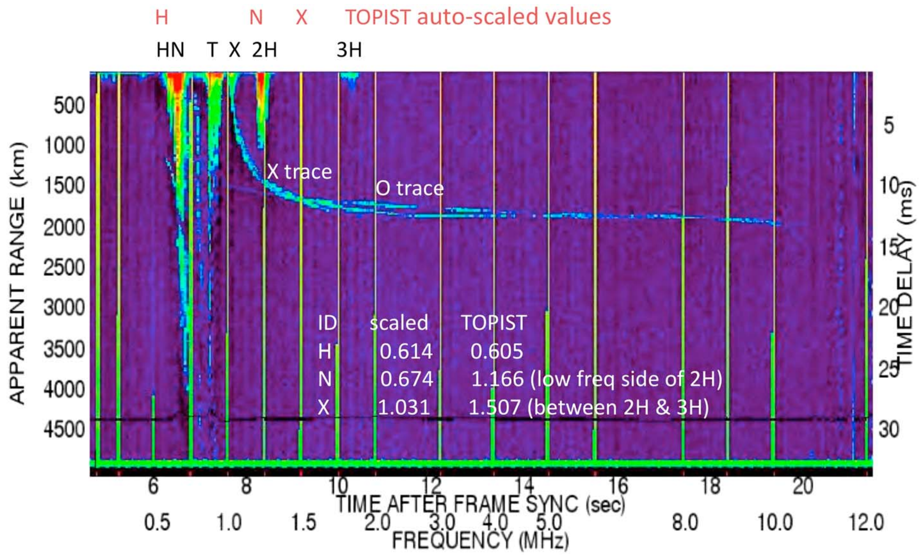

Figure 9. Same as Figure 8 except for the Ottawa ionogram recorded at 1415:52 on day 50 of 1969 corresponding to the one used for the left panel of Figure 7. (2,011-km HGT, 0919 GMLTM, 43.4° GMLAT, −5.0° GMLONG, 51.7 INVLAT.) TOPIST = Topside Ionogram Scaler with True height algorithm.

The third approach was to manually scale the ionospheric reflection traces on the ISIS-I *av2* digital ionograms used to produce the TOPIST auto-scaled profiles in the left panel of Figure 11. The Jackson (1969a) inversion routine, within the Burgess ISIS ionogram analysis software (available from the NASA/GSFC SPDF), was used to derive the topside $N_e(h)$ profiles. The resulting profiles are presented in the left panel of Figure 12 and again in the right panel of Figure 12 with the addition of the corresponding profiles from IRI-2016. Note how the manual scaling results of this figure correct the erroneous TOPIST auto-scaling of profiles 1, 2, 3, 5, and 8 in Figure 11.

Thus, all 12 of the ISIS-I *av2* topside digital ionograms listed in Table 1 were capable of producing accurate topside $N_e(h)$ profiles, as indicated by the manual scaling results presented in Figure 12, but only seven of them could be correctly auto-processed by the TOPIST software (profiles 4, 6, 7, and 9–12 in Figure 11). The erroneous auto-processing of the other five ionograms (leading to profiles 1, 2, 3, 5, and 8 in Figure 11) was the result of the misidentification of sounder-stimulated plasma resonances and wave cutoff frequencies that led to incorrect onsets of the $N_e(h)$ profiles at the satellite altitude. Figure 12 clearly illustrates the increasing departure of the IRI-2016 model from the true N_e with increasing altitude as discussed in connection with the right panel of Figure 11.

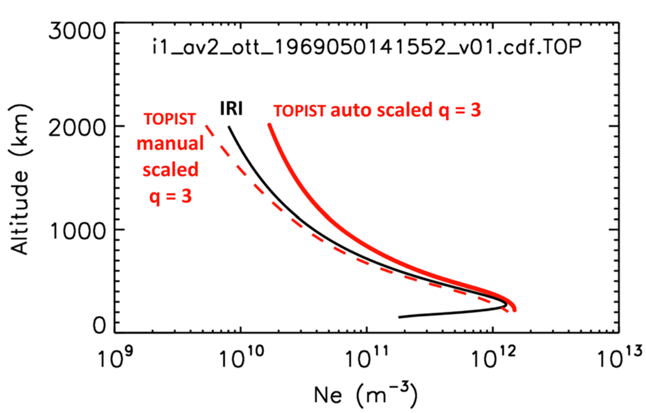

Figure 10. Same as the left panel of Figure 7 with the addition of the TOPIST manual-scaled profile. IRI = International Reference Ionosphere; TOPIST = Topside Ionogram Scaler with True height algorithm.

Next the full data set of more than 8,000 TOPIST $N_e(h)$ OTT profiles obtained between 1969 and 1983 was investigated. A histogram of the occurrence of these profiles against the day of year showed a peak in early December between days 335 and 345, and within that date interval, there was another occurrence peak with magnetic latitude between 45° and 50°. All of the available TOPIST $N_e(h)$ OTT profiles from these intervals are plotted in the left panel of Figure 13. These data were restricted into two narrow time windows, again based on the availability of a large number of profiles, in the middle and right panels of Figure 13. The predicted IRI-2016 profiles for these two intervals are also shown (easiest to identify by following the only curves that include a bottomside profile). A large spread in the early morning profiles is observed in the middle panel during the 1-hr window centered on 04:00 magnetic local time, and most of them are significantly above the IRI-2016 predictions. A much tighter grouping of the profiles is observed in the right panel during the 1-hr window centered on 12:00 magnetic local time, and most of them straddle the IRI-2016

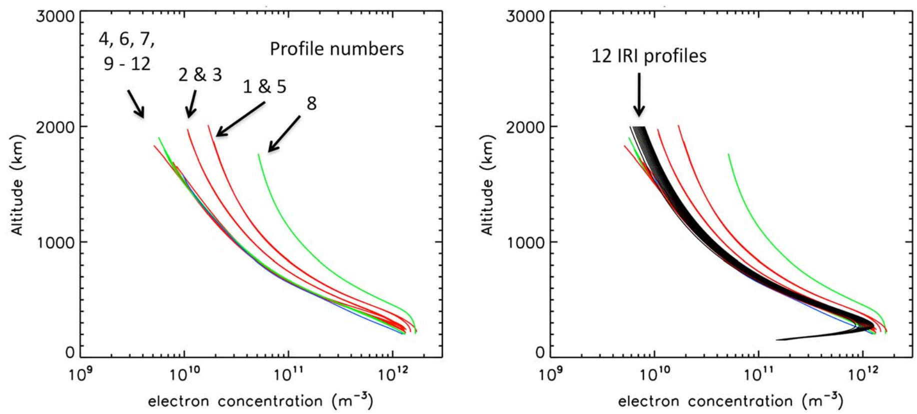

Figure 11. (left) Topside Ionogram Scaler with True height algorithm $N_e(h)$ profiles from 12 Ottawa International Satellites for Ionospheric Studies-I topside ionograms from the satellite pass over Ottawa on day 50 (19 February) of 1969 from 1415:52 to 1421:44 UT in blue, green, and red for q = 1, 2, and 3, respectively. The profile numbers refer to the information given in Table 1. The three profiles from Figures 6 and 7 recorded on this day are included (profiles 11 and 12 correspond to the left and right panels of Figure 6, respectively; profile 1 corresponds to the left panel of Figure 7). (right) The same selection of profiles with the addition of the corresponding 12 IRI-2016 profiles (black curves). IRI = International Reference Ionosphere.

predictions in the 1,000- to 2,000-km altitude region. The plasma resonances and wave cutoffs were scaled on several ISIS-I *av2* ionograms corresponding to representative profiles (labels in the middle and right panels) to determine $[(N_e)_{sat}]_{res}$ values and compare them to the values $[(N_e)_{sat}]_{topist}$ at the top of the TOPIST profiles near 3,000-km altitude.

In the middle panel of Figure 13, the ratio $[(N_e)_{sat}]_{topist}/[(N_e)_{sat}]_{res}$ was 0.52, 1.2, 2.4, and 2.9 for the curves labeled 1, 2, 3, and 4, respectively. The top of the TOPIST profile labeled 2 was the closest to the observed $[(N_e)_{sat}]_{res}$ value of 2.1×10^9 m^{-3}, the lower profile (1) was about one half the observed value of 3.1×10^9 m^{-3}, and the two higher profiles (3 and 4) were considerably above their observed values (of 2.4×10^9 and 3.1×10^9 m^{-3}, respectively). Thus, the most likely $[(N_e)_{sat}]_{res}$ value is between 2×10^9 and 3×10^9 m^{-3} near 3,000 km during these early morning winter conditions, considerably above what an extrapolation of the IRI-2016 value of 2×10^9 m^{-3} at 2,000 to 3,000 km would yield. Based on these comparisons with the manually measured values, it appears that the scatter in the TOPIST profiles in the middle panel of Figure 12 may be due more to problems with the TOPIST auto-processing than to N_e variations.

Table 1

The Universal Times on Day 50 of 1969 of the 12 Topside $N_e(h)$ Profiles of Figure 11 (Followed by an r, g, or b Designating the Red, Green, or Blue Curves, Respectively, in Figure 11) and the Corresponding Values of $[(N_e)_{sat}]_{res}$, $[(N_e)_{sat}]_{topist}$, $[(N_e)_{sat}]_{iri}$ in Electrons Per Cubic Meter and the Percentage Increases of $[(N_e)_{sat}]_{topist}$, and $[(N_e)_{sat}]_{iri}$ Above $[(N_e)_{sat}]_{res}$ Based on the 12 International Satellites for Ionospheric Studies-I Ionograms With Start Times From 1415:52 to 1421:44 as the Satellite Descended From an Altitude of 2,005 to 1,590 km

Profile	UT	$[(N_e)_{sat}]_{res}$ (m^{-3})	$[(N_e)_{sat}]_{top}$ (m^{-3})	$[(N_e)_{sat}]_{iri}$ (m^{-3})	(top-res)/res (%)	(iri-res)/res (%)
1	1415:52 r	5.6×10^9	1.7×10^{10}	7.9×10^9	204	41
2	1416:21 r	4.9×10^9	1.1×10^{10}	7.9×10^9	124	61
3	1416:51 r	4.9×10^9	1.1×10^{10}	8.1×10^9	124	65
4	1417:20 g	4.9×10^9	5.7×10^9	8.1×10^9	16	65
5	1417:49 r	5.1×10^9	1.9×10^{10}	8.3×10^9	273	63
6	1418:19 r	5.2×10^9	5.1×10^9	8.3×10^9	2	60
7	1418:48 g	5.7×10^9	6.4×10^9	8.5×10^9	12	49
8	1419:17 g	6.25×10^9	5.1×10^{10}	8.5×10^9	716	36
9	1419:47 r	6.4×10^9	7.2×10^9	8.75×10^9	13	37
10	1420:16 r	7.0×10^9	7.7×10^9	8.75×10^9	10	25
11	1420:45 r	7.7×10^9	8.3×10^9	9.0×10^9	8	17
12	1421:44 b	8.4×10^9	9.6×10^9	9.2×10^9	14	10

Note. The satellite altitude determines the upper limit of the Topside Ionogram Scaler with True height algorithm profiles in Figure 11; the International Reference Ionosphere 2016 profiles all extend up to the 2,000 km upper limit of the model.

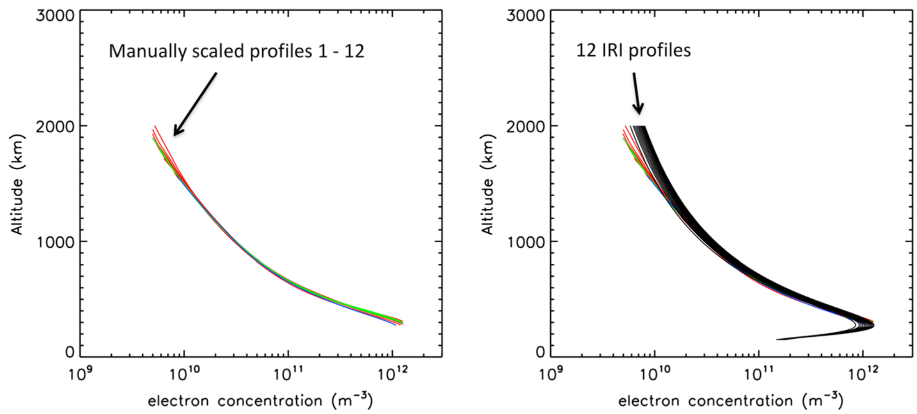

Figure 12. (left) Topside N_e(h) profiles based on the manual scaling of the 12 International Satellites for Ionospheric Studies-I *av2* ionograms used to produce the Topside Ionogram Scaler with True height algorithm auto-processed N_e(h) profiles of Figure 11. (right) Same with the addition of the corresponding 12 IRI-2016 profiles. IRI = International Reference Ionosphere.

In the right panel of Figure 13, the $[(N_e)_{sat}]_{res}$ values were 1.5×10^9 and 3.2×10^9 m^{-3}, and the corresponding $[(N_e)_{sat}]_{topist}/[(N_e)_{sat}]_{res}$ ratios were 4.0 and 3.3 for the curves labeled 1 and 2, respectively. Extrapolating the IRI-2016 profile, above its current 2,000-km altitude limit, to altitudes corresponding to the tops of the TOPIST profiles would yield a predicted N_e value considerably above the observed $[(N_e)_{sat}]_{res}$ values. Thus, the IRI-2016 noontime winter midlatitude prediction would be too high.

The above conclusions, concerning the accuracy of selected auto-scaled TOPIST profiles in Figure 13 and their relationship to IRI-2016 predictions, were based on scaling the plasma resonances and wave cutoffs on the corresponding ionograms. These selected ISIS-1 *av2* ionograms were also manually scaled, using the same procedure as for the ionograms of Figure 11, and the results are presented in Figure 14. The tops of the profiles are shifted as expected based on the results of the scaling of the resonances and cutoffs discussed above. The $(N_e)_{max}$ values at the lowest altitudes were checked by comparing them to the hourly values determined from the Ottawa ground-based ionosonde at the times appropriate to the ISIS-I ionogram times (see caption of Figure 13). The ionosonde $(N_e)_{max}$ values at 0900 and 1000 UT on 10 December 1981, appropriate for the left panel of Figure 14, were 3.75×10^{11} m^{-3}. These values are considerably higher than either

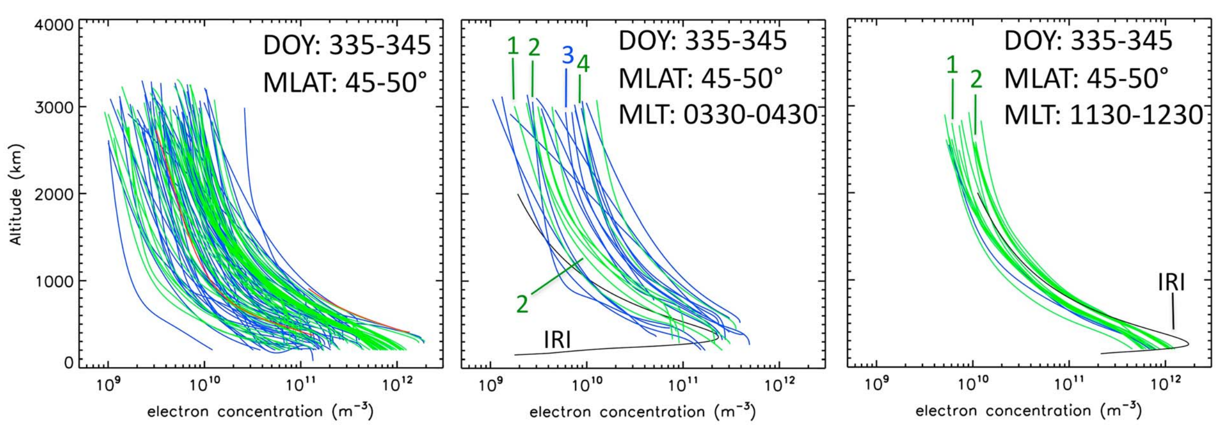

Figure 13. (left) A subset of the Topside Ionogram Scaler with True height algorithm N_e(h) profiles from the Ottawa 1969–1983 data set restricted to the interval from 1 to 11 December and also restricted to MLAT between 45° and 50° using blue, green, and red for 112 profiles with q = 1, 2, and 3, respectively. (middle) Same but for 23 profiles resulting from the added restriction of MLT between 0330 and 0430 and the addition of the IRI-2016 profile for the central time. (right) Same as the middle panel except for 17 profiles resulting from the restriction of MLT between 1130 and 1230. The labels on the profiles in the middle and right panels are discussed in the text. The numbered Topside Ionogram Scaler with True height algorithm profiles in the middle panel are all from day 344 (10 December) of 1981 at the following universal times: 0919:52, 0920:48, 0921:15, and 0920:20 for profiles 1, 2, 3, and 4, respectively; those in the right panel are from day 337 (3 December) of 1969 at 1935:42 and 1934:17 for profiles 1 and 2, respectively. IRI = International Reference Ionosphere.

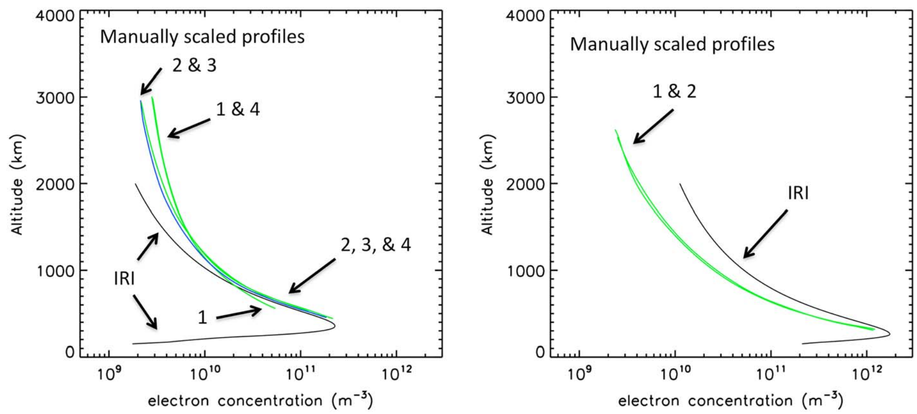

Figure 14. (left) Topside N_e(h) profiles based on the manual scaling of the four International Satellites for Ionospheric Studies-I *av2* ionograms used to produce the Topside Ionogram Scaler with True height algorithm auto-processed N_e(h) profiles labeled 1–4 in the middle panel of Figure 13. The appropriate IRI-2016 N_e(h) profile is included as a black curve. (right) Same except for the profiles labeled 1 and 2 in the right panel of Figure 13. IRI = International Reference Ionosphere.

the IRI-2016 or the manually scaled values (ranging from 5.4×10^{10} to 2.2×10^{11} m^{-3}), but ISIS-I was well below the Ottawa ionosonde latitude of 45° during the recording of the four ionograms used in the left panel of Figure 14 (ranging from 33.6° to 36.8°). The ionosonde $(N_e)_{max}$ values at 1900 and 2000 UT on 3 December 1969, appropriate for the right panel of Figure 14, were 1.2 and 1.3×10^{12} m^{-3} in good agreement with the manually scaled values of 1.2×10^{12} m^{-3}; in this case ISIS-I was closer to the Ottawa ionosonde latitude during the recording of the two ionograms used in the right panel of Figure 14 (ranging from 33.7° to 40.2°).

The results of this section emphasize the need for reliable topside N_e(h) profiles extending to high altitudes, as can be obtained from the ISIS-I satellite, for the improvement of IRI-2016. Unfortunately, the results also indicate that the present version of the TOPIST software does not produce these profiles from the version-2 ISIS-I digital ionograms, that is, the *av2* ionograms, with sufficient confidence to fulfill this need. Based on the inspection of the sounder-stimulated plasma resonances and wave cutoffs and the manual scaling of the ionospheric reflection traces on the selected ionograms, it appears that the first priority for improving the TOPIST performance in the processing of version-2 ISIS-I digital topside ionograms is to improve the detection scheme for identifying sounder-stimulated plasma resonances and wave cutoffs in order to automatically obtain accurate $[(N_e)_{sat}]_{res}$ values. Such an improvement is possible if the software includes the expected resonant characteristics, and spectral patterns, for different values of the ratio of the electron plasma frequency to the electron gyrofrequency; these spectral patterns should include the resonances known as the Dn and Qn resonances observed between the harmonics of the electron gyrofrequency (Benson, 1982; Osherovich & Benson, 1991).

5. Summary

The four Alouette/ISIS topside sounder satellites combined to produce 60 satellite years of swept-frequency topside ionospheric sounding spanning the time interval from 1962 to 1990. During the 1960s and 1970s, skilled operators hand scaled approximately 177,000 of the millions of 35-mm film ionograms to produce vertical N_e(h). An A/D conversion project in the 1990s and 2000s led to more than 588,000 digital topside ionograms from the original Alouette-2, ISIS-I, and ISIS-II analog telemetry tapes. Automatic processing by the TOPIST software was attempted on all of the ISIS-II digital ionogram files. Not all of them could be automatically processed, due to problems encountered during the earlier A/D operation, but more than 86,000 files yielded topside N_e(h) profiles. An ISIS-I data enhancement project is underway to correct the problems encountered during the A/D operation in order to maximize the number of files capable of TOPIST automatic processing. These problems were mainly caused by the lack of proper frame-sync detection on many of the ionograms. During the first phase of this project, all of the digital ionograms from the Ottawa telemetry station were converted to version-2 files (more than 80,000 files from 1969 to 1983). During the current phase, more than 20,000 version-2 files from the Quito and the University of Alaska telemetry stations have been produced.

The version-2 ISIS-I topside digital ionogram files, also designated as *av2* files, recover frequency information often missing in the original digital ionogram files. This recovered frequency information allows the digital ionogram files to be scaled manually and also makes them capable of automatic processing by software such as TOPIST.

Many of the OTT version-2 ISIS-I files have been processed by the TOPIST software to produce topside $N_e(h)$ profiles. Some of the TOPIST automatically produced ISIS-I profiles were checked by inspecting the corresponding version-2 ISIS-I topside digital ionograms. The plasma resonances and wave cutoffs were scaled on these ionograms to determine $[(N_e)_{sat}]_{res}$ values, the reflection traces were manually scaled to obtain accurate topside $N_e(h)$ profiles, and foF2 values from the Ottawa ground-based ionosonde were used to calculate $(N_e)_{max}$ values for comparison with the N_e values at the bottom of the manually scaled $N_e(h)$ profiles. In many cases large differences were observed between the $[(N_e)_{sat}]_{res}$ values and the values at the top of the TOPIST profiles. These differences indicate the need to improve the portion of the TOPIST software dedicated to the identification of sounder-stimulated plasma resonances and wave cutoffs at the satellite location. Proper identification of these features is crucial for obtaining the correct starting points for the inversion of topside ionospheric reflection traces into accurate topside $N_e(h)$ profiles.

The manually determined $[(N_e)_{sat}]_{res}$ values and the manually produced topside $N_e(h)$ profiles were also compared with the IRI-2016 model predictions. During one late morning, midlatitude winter ISIS-I satellite pass in 1969 IRI-2016 was found to predict higher N_e values at the satellite altitude. The differences ranged from about 60% when the satellite was near 2,000 km to within about 30% when it approached 1,600 km. In another investigation, involving thousands of ISIS-I TOPIST auto-produced $N_e(h)$ topside profiles collected over many years during midlatitude winter conditions, selected profiles for manual scaling to produce $[(N_e)_{sat}]_{res}$ values indicated that IRI-2016 predicted N_e values at the satellite altitude that were too high at noon in 1969 but too low in early morning in 1981.

Acknowledgments
This work was supported by the NASA Data Services Upgrade Program (NNH13ZDA001N-HIDEE and NNH15ZDA001N-HIDEE). V. T. was supported, in part, by grant LTAUSA17100 of the Ministry of Education, Youth and Sports of the Czech Republic. The version-2 ISIS-I topside digital ionogram files (designated as *av2*) are available from ftp://cdaweb.gsfc.nasa.gov/pub/data/isis/topside_sounder/ionogram_new_i1_cdf/isis1/. The ISIS-I TOPIST files are available from https://spdf.gsfc.nasa.gov/pub/data/isis/topside_sounder/topist_ne_profile_ascii/OTT_45N_284E/. The CDAWeb data display service and the Burgess ISIS ionogram analysis software are available from the ISIS data restoration project home page at http://spdf.gsfc.nasa.gov/isis/isis-status.html. The ground-based Ottawa ionosonde foF2 values were obtained from http://spidr.ionosonde.net/spidr/. The authors are grateful to Philip Chu and Jonathan Tsang for assistance in data corrections, to Mohamed Osman for assistance with the TOPIST processing, and to the reviewers for their critical reading of the paper and helpful comments.

References

Benson, R. F. (1982). Stimulated plasma instability and nonlinear phenomena in the ionosphere. *Radio Science*, *17*(6), 1637–1659. https://doi.org/10.1029/RS017i006p01637

Benson, R. F. (1996). Ionospheric investigations using digital Alouette/ISIS topside ionograms. In J. M. Goodman (Ed.), *1996 Ionospheric Effects Symposium* (pp. 202–209). Alexandria, Virginia: Technology for Communications International/BR Communications.

Benson, R. F., & Bilitza, D. (2009). New satellite mission with old data: Rescuing a unique data set. *Radio Science*, *44*, RS0A04. https://doi.org/10.1029/2008RS004036

Benson, R. F., Fainberg, J., Osherovich, V. A., Truhlik, V., Wang, Y., Bilitza, D., & Fung, S. F. (2016). High-latitude topside ionospheric vertical electron density profile changes in response to large magnetic storms. *Radio Science*, *51*, 524–537. https://doi.org/10.1002/2015RS005882

Benson, R. F., Truhlik, V., Huang, X., Wang, Y., & Bilitza, D. (2012). Improving the automatic inversion of digital Alouette/ISIS ionogram-reflection traces into topside electron-density profiles. *Radio Science*, *47*, RS0L04. https://doi.org/10.1029/2011RS004963

Bilitza, D., Altadill, D., Truhlick, V., Shubin, V., Galkin, I., Reinisch, B., & Huang, X. (2017). International Reference Ionosphere 2016; from ionospheric climate to real-time weather predictions. *Space Weather*, *15*, 418–429. https://doi.org/10.1002/2016SW001593

Bilitza, D., Huang, X., Reinisch, B. W., Benson, R. F., Hills, H. K., & Schar, W. B. (2004). Topside Ionogram Scaler with True height algorithm (TOPIST): Automated processing of ISIS topside ionograms. *Radio Science*, *39*, RS1S27. https://doi.org/10.1029/2002RS002840

Hoegy, W. R., & Benson, R. F. (1988). DE/ISIS conjunction comparisons of high-latitude electron density features. *Journal of Geophysical Research*, *93*(A6), 5947–5954. https://doi.org/10.1029/JA093iA06p05947

Huang, X., Reinisch, B. W., Bilitza, D., & Benson, R. F. (2002). Electron density profiles of the topside ionosphere. *Annales de Geophysique*, *45*(1), 125–130.

Jackson, J. E. (1969a). The reduction of topside ionograms to electron-density profiles. *Proceedings of the IEEE*, *57*(6), 960–976. https://doi.org/10.1109/PROC.1969.7140

Jackson, J. E. (1969b). Comparisons between topside and ground-based soundings. *Proceedings of the IEEE*, *57*(6), 976–985. https://doi.org/10.1109/PROC.1969.7141

Jackson, J. E. (1986). Alouette-ISIS program summary *Rep. NSSDC Report 86-09*, NSSDC Report 86-09. Greenbelt, MD: National Space Science Data Center.

Jackson, J. E., & Warren, E. S. (1969). Objectives, history, and principal achievments of the topside sounder and ISIS programs. *Proceedings of the IEEE*, *57*(6), 861–865. https://doi.org/10.1109/PROC.1969.7130

Muldrew, D. B. (2006). The Poynting vector applied to the complex refractive index in a hot plasma near the electron-cyclotron frequency, and to the cyclotron resonance observed on topside ionograms. *Radio Science*, *41*, RS6006. https://doi.org/10.1029/2006RS003496

Osherovich, V. A., & Benson, R. F. (1991). The lower subsidiary diffuse plasma resonances and the classification of radio emissions below the plasma frequency. *Journal of Geophysical Research*, *96*(A11), 19,331–19,341. https://doi.org/10.1029/91JA01961

Reinisch, B. W., Nsumei, P., Huang, X., & Bilitza, D. K. (2007). Modeling the F2 topside and plasmasphere for IRI using IMAGE/RPI, and ISIS data. *Advances in Space Research*, *39*(5), 731–738. https://doi.org/10.1016/j.asr.2006.05.032.

Sethi, N. K., Dabas, R. S., & Sharma, K. (2008). Comparison between IRI predictions and digital ionosonde measurements of hmF2 at New Delhi during low and moderate solar activity. *Journal of Atmospheric and Solar - Terrestrial Physics*, *70*(5), 756–763. https://doi.org/10.1016/j.jastp.2007.10.009

Themens, D. R., Jayachandran, P. T., Nicolls, M. J., & MacDougall, J. W. (2014). A top to bottom evaluation of IRI 2007 within the polar cap. *Journal of Geophysical Research: Space Physics*, *119*, 6689–6703. https://doi.org/10.1002/2014JA020052

Wang, Y., Benson, R. F., Bilitza, D., Fung, S. F., Chu, P., Huang, X., & Truhlik, V. (2015). Data Services Upgrade: Perfecting the ISIS-1 topside digital ionogram database. Paper presented in Proceedings of the 14th International Ionospheric Effects Symposium IES2015, edited by K. M. Groves, Alexandria, Virginia, 12-14 May 2015.

Whitteker, J. H., Brace, L. H., Maier, E. J., Burrows, J. R., Dodson, W. H., & Winningham, J. D. (1976). A snapshot of the polar ionosphere. *Planetary and Space Science*, *24*(1), 25–32. https://doi.org/10.1016/0032-0633(76)90057-X