Status of and scientific results from the ISIS-I Topside Digital Ionogram Data Enhancement Project

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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 TOPIST 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 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 present the status of, and results from, this ongoing enhancement effort.

1. INTRODUCTION

The four polar-orbiting Canadian-built and U.S. launched topside-sounder satellites Alouette 1, Alouette 2, ISIS I, and ISIS II were included in the six-satellite International Satellites for Ionospheric Studies (ISIS) program; the other two were the U.S. Explorer 20 and Explorer 31 satellites [*Jackson*, 1986; *Jackson and Warren*, 1969]. 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 7-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 (GSFC) 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 and 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]. Many of the ISIS-II digital ionograms could not be auto-processed due to problems encountered during the A/D operation. In addition, some files that were auto-processed yielded erroneous topside $N_e(h)$ due to incorrect starting conditions in the identification of ionospheric reflection traces; this situation led to improvements in the TOPIST software [*Benson et al.*, 2012]. A data-enhancement project was then initiated to correct problems that often occurred during the A/D process so as to increase the TOPIST success rate [*Benson et al.*, 2012; *Wang et al.*, 2015]. First priority was given to ISIS I because of the large number of digital ionograms available, the data time span from 1969 to 1982, 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 (ISIS II was in a circular 1,400-km orbit) where predictions based on the International Reference Ionosphere (IRI) [*Bilitza*, 2009] are in great need of improvement.

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 1a). Only slightly more than 1/3 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 (see caption). 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, etc., they will not contain swept-frequency ionospheric reflection traces to invert into $N_e(h)$. In addition, some of the 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).

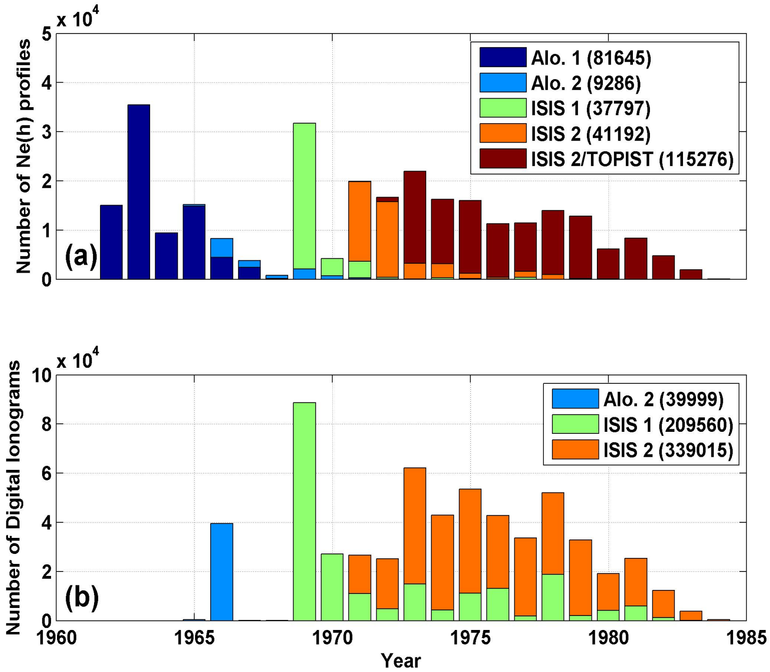

Figure 1. Data sets available from the NASA Space Physics Data Facility (SPDF) at http://spdf.gsfc.nasa.gov/isis/isis-status.html as of January 2009: (a) manually-scaled topside $N_e(h)$ from Alouette-1, Alouette-2, ISIS-I, and ISIS-II 35-mm film topside ionograms and the number of digital files resulting 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 Figure 1a). Unfortunately, the label in Figure 1a is not correct in the case of ISIS II since all of the files processed by TOPIST did not yield $N_e(h)$ results; see Figure 2, and the discussion in the caption and text, for the correct number of ISIS-II TOPIST $N_e(h)$ broken down by quality codes. (Figure after [*Benson and Bilitza*, 2009].)

TOPIST could not process many of the ISIS-II digital ionogram files and it was often not clear why the processing failed. There were 4 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 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. The distributions of these four possible outcomes over all the years covered by the ISIS-II digital ionogram data are presented in Figure 2. The totals indicate that when TOPIST could automatically process ISIS-II ionograms to produce $N_e(h)$ that 60.5% of these profiles were either of medium or high quality, i.e., with q = 2 or 3.

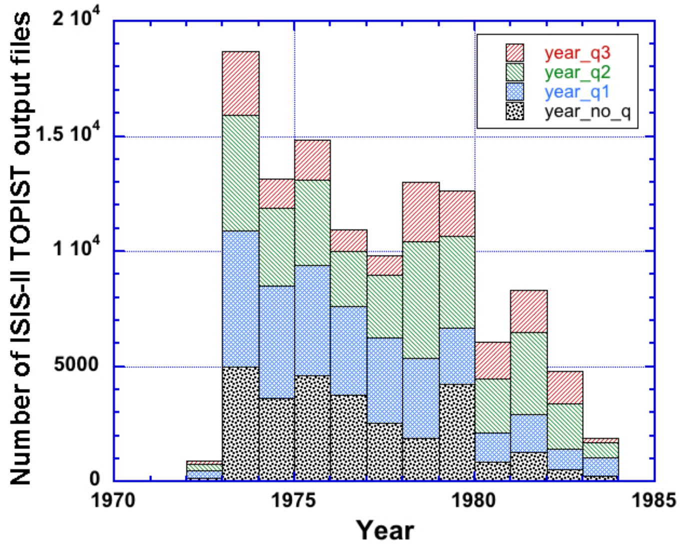

Figure 2. Number of ISIS-II TOPIST $N_e(h)$, broken down by quality codes: q=3 (highest quality; upper red-shaded areas), q = 2 (medium quality; next-lower green-shaded areas), q = 1 (lowest quality; next-lower blue-shaded areas), or "no q" (or a q value but defective data so that no $N_e(h)$ produced; the lowest black-shaded areas). 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), i.e., without $N_e(h)$ profiles, for a total of 115,270 (the total given in Figure 1a included 6 TOPIST files with zero size).

The large digital topside ionogram database, indicated in Figure 1b, has enabled efficient search procedures 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, i.e., the resonance at the electron gyrofrequency [*Muldrew*, 2006]. This large digital topside ionogram database, and the large topside $N_e(h)$ database indicated in Figure 1a, has 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]. The large TOPIST $N_e(h)$ database has been used, together with higher-altitude profiles obtained by the Radio Plasma Imager (RPI) 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

We are currently producing version-2 ISIS-I topside digital ionograms to be accessible from the SPDF CDAWeb system and from the NASA Heliophysics Virtual Wave Observatory (VWO). A major goal is to produce as many topside ionospheric $N_e(h)$ as possible so as to expand the $N_e(h)$ profile coverage in latitude, longitude, and epoch available from the NASA/SPDF. First priority was given to producing more than 80,000 version-2 digital topside ionogram files for all of the available years of ISIS-I data from the Ottawa (OTT) telemetry station (from 1969-1983) [*Wang et al.*, 2015]. Currently, we are processing ISIS-I digital topside ionogram files from the Quito (QUI), University of Alaska (ULA), and Santiago (SNT) telemetry stations. Figures 3 – 5, obtained from CDAWeb displays, 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 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 $N_e(h)$.

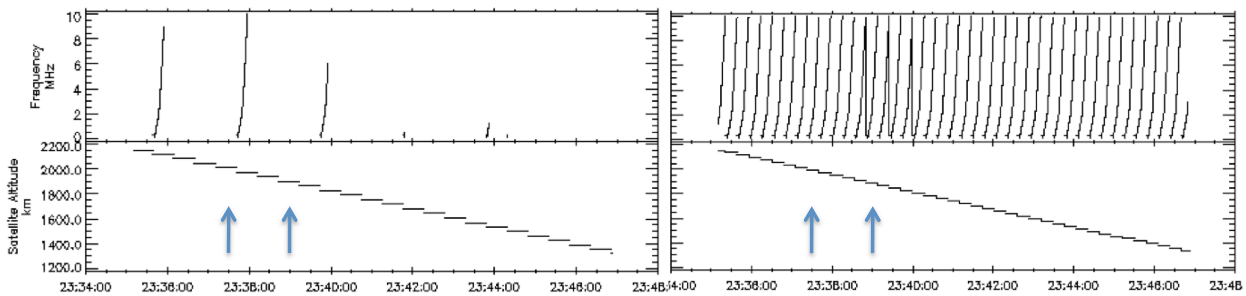

Figure 3. Comparing available frequency information (0.1 to 10 MHz in the top panels) and file start times (each at a different altitude in the range from 1,200 to 2,200 km in the bottom panels) for av (left panels) and av2 (right panels) for OTT ISIS-I data from 2334 to 2348 UT on 25 January 1976. The 1½-minute portions between the arrows are presented in Figure 4 with the addition of sounder data.

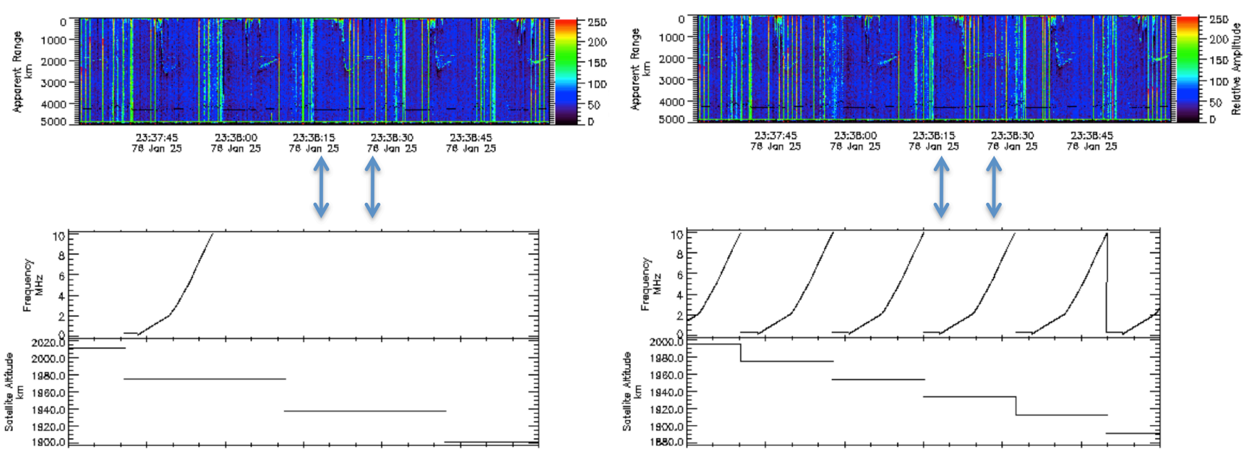

Figure 4. Same as Figure 3 except for only the OTT ISIS-I data from 2337:30 to 2339:00 UT on 25 January 1976, the altitude scales are different, and the sounder data appear in the top panels. The 10 s portions between the arrows are expanded in Figure 5.

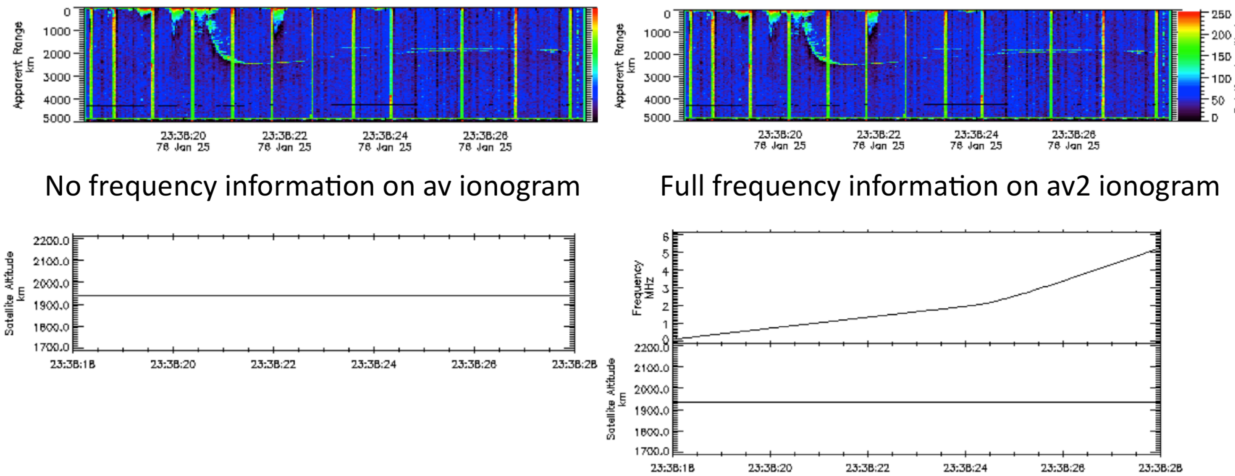

Figure 5. Same as Figure 4 except for only the 10 s intervals of swept-frequency operation from 0.1 to 5 MHz during the OTT ISIS-I av (left) and av2 (right) ionograms from 2338:18 to 2338:28 UT on 25 January 1976. The altitude is the value at the start of the file.

4. RESULTS USING VERSION-2 ISIS-I IONOGRAMS

Many of the version-2 ISIS-I digital topside ionograms have been processed by TOPIST and the resulting $N_e(h)$ have been compared with those obtained from IRI2016. Some sample comparisons are given in Figure 6 and 7, for each q value, when the agreement in the topside ionosphere is good and not good, respectively. More such comparisons are planned, particularly for cases with q = 2 and 3, to determine the conditions that most often lead to good agreement and those that lead to poor agreement.

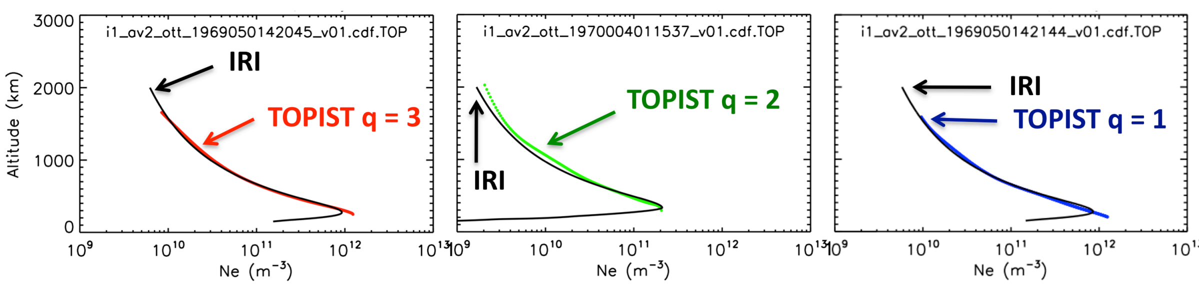

Figure 6. TOPIST $N_e(h)$ examples with q = 3 (left), 2 (middle), and 1 (right) with good topside agreement.

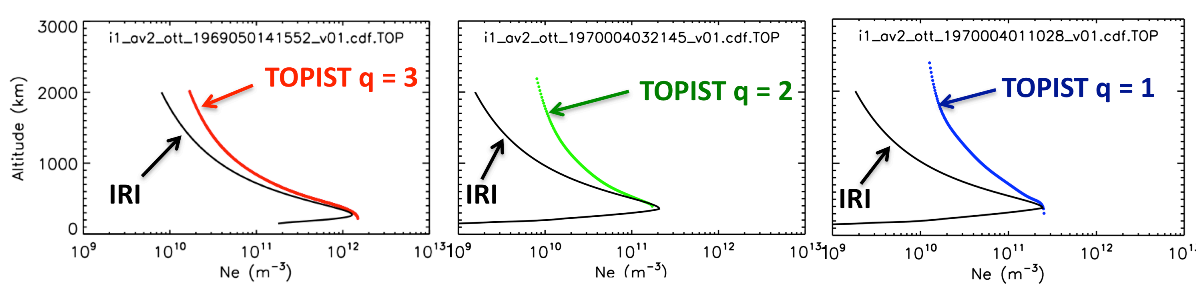

Figure 7. Same as Figure 6 except for TOPIST $N_e(h)$ examples where the agreement with IRI in the topside ionosphere is not good.

5. SUMMARY

The 4 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 analog-to-digital 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; all of the ISIS-II digital ionograms were automatically processed by the TOPIST software and more than 86,000 yielded topside $N_e(h)$. An ISIS-I data enhancement project is underway to correct problems encountered during the A/D operation in order to maximize the number of files capable of processing by TOPIST. 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 1969-1983). During the current phase, files from the Quito, University of Alaska, and Santiago telemetry stations are being converted to version-2 files. Many of the version-2 files have been processed by the TOPIST software to produce topside $N_e(h)$. These vertical profiles have been compared with the IRI2016 model and examples were presented both when the agreement in the topside ionosphere was very good and when it was not good. In the later case the TOPIST $N_e(h)$ values at high altitudes were considerably greater than the IRI2016 values; examples were shown where the differences were a factor of 2 or more at an altitude of 2,000 km.

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