

## Data Services Upgrade: Perfecting the ISIS-I topside digital ionogram database

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### ABSTRACT

The ionospheric topside sounders of the International Satellites for Ionospheric Studies (ISIS) program were designed as analog systems. More than 16,000 of the original telemetry tapes from three satellites were used to produce topside digital ionograms, via an analog-to-digital (A/D) conversion process, suitable for modern analysis techniques. Unfortunately, many of the resulting digital topside ionogram files could not be auto-processed to produce topside  $N_e(h)$  profiles because of problems encountered during the A/D process. Software has been written to resolve these problems and here we report on (1) the first application of this software to a significant portion of the ISIS-1 digital topside-ionogram database, (2) software improvements motivated by this activity, (3)  $N_e(h)$  profiles automatically produced from these corrected ISIS-1 digital ionogram files, and (4) the availability via the Virtual Wave Observatory (VWO) of the corrected ISIS-1 digital topside ionogram files for research. We will also demonstrate the use of these  $N_e(h)$  profiles for making refinements in the International Reference Ionosphere (IRI) and in the determination of transition heights from  $O^+$  to  $H^+$ .

### 1. INTRODUCTION

The ionospheric topside sounder on the ISIS-1 satellite was designed as an analog system, as were the other ionospheric radio sounders included in the International Satellites for Ionospheric Studies (ISIS) program. The plan was to display the data on 35-mm film for analysis by visual inspection. The long operational lifetime of ISIS 1 (21 years) and cost considerations, however, prevented all of the sounder data from being converted to such film records. After the termination of the ISIS program in 1990, more than 16,000 of the original telemetry tapes from three of the topside-sounder satellites (Alouette 2, ISIS 1, and ISIS 2) were converted directly into digital records. The goal was to select a large number of telemetry tapes that were never processed to produce 35-mm film topside ionograms and to use them to produce topside digital ionograms suitable for modern analysis techniques, thus essentially creating new satellite missions with old data [Benson and Bilitza, 2009]. See also the web page for the ISIS/Alouette Topside Sounder

Data Restoration Project home page at [spdf.gsfc.nasa.gov/isis/isis-status.html](http://spdf.gsfc.nasa.gov/isis/isis-status.html). Based on experience gained with ISIS 2, the analog-to-digital (A/D) conversion process was modified for ISIS 1 in an attempt to increase the number of digital topside ionograms that could be successfully auto-processed to produce topside vertical electron-density profiles  $N_e(h)$ . The TOPIST algorithm (TOPside Ionogram Scaler with True-height) [Bilitza *et al.*, 2004; Huang *et al.*, 2002], developed for the ISIS-2 digital topside ionograms, was modified so as to be able to automatically process the more-recently produced ISIS-1 digital topside ionograms. As with ISIS 2, however, many of the digital ISIS-1 topside ionogram files could not be auto-processed by TOPIST to produce topside  $N_e(h)$  profiles because of problems with the digital files. Software has been written to resolve these problems, which originated during the earlier A/D process, as described in Benson *et al.* [2012]. In the following sections we first illustrate the problems being addressed. Next we describe the software used to correct these problems and illustrate the results of these corrections. Finally we will present topside  $N_e(h)$  profiles, automatically-produced using the TOPIST software on the corrected ISIS-1 ionogram files, and illustrate the application of these profiles in refining the International Reference Ionosphere (IRI) and in determining  $O^+/H^+$  transition heights.

## **2. TOPSIDE-IONOGRAM A/D CONVERSION-PROCESS PROBLEMS**

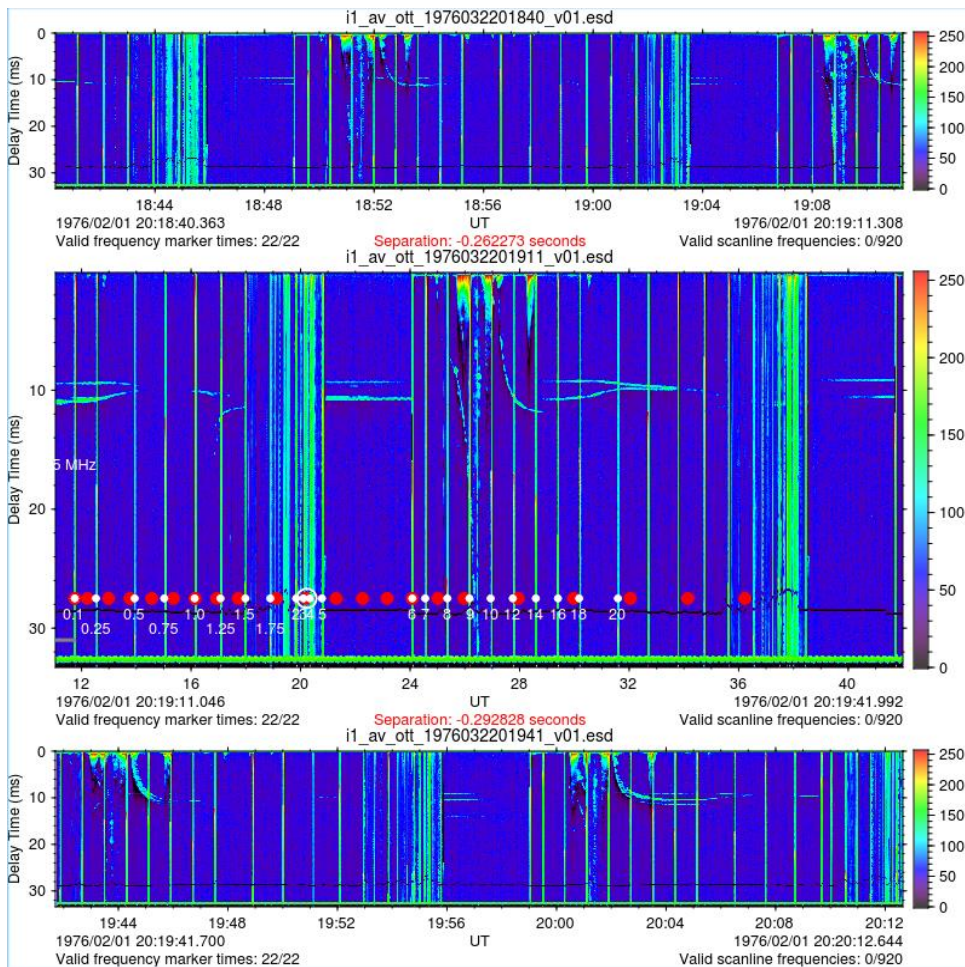
Several problems were encountered during the A/D conversion of the ionogram data contained on the original 7-track analog telemetry tapes. These include timing errors in the data files and, at times, the lack of proper detection of ionogram frame-sync pulses and frequency markers. Timing errors were caused by bit-code errors in reading the time code during the A/D process resulting in incorrect spacecraft position and magnetic field information. Some of these erroneous values could easily be detected as described at [spdf.gsfc.nasa.gov/isis/isis-status.html](http://spdf.gsfc.nasa.gov/isis/isis-status.html). Other timing problems were caused by variations in the speeds of the tape drives used in the recording and play back of the telemetry data. When the ionogram frame sync pulse was not properly detected then, in most cases, the frequency marks were also not properly detected and programs such as TOPIST could not automatically process the ionospheric reflection traces into topside  $N_e(h)$  profiles. Even when frame syncs were properly identified, proper frequency-marker identification was not always guaranteed because of interference signals and strong plasma resonances that could be falsely identified as frequency markers during the A/D process. An experienced observer can often easily correct these problems but it is desirable to have software capable of increasing the efficiency of the process. The next section will illustrate the correction procedure.

## **3. SOFTWARE-AIDED MANUAL CORRECTION OF PROBLEMS**

Software was developed to aid in detecting timing-overlap problems, fixing frame-sync detection problems, identifying frequency marks, and for the interpolation between frequency markers to assign the proper frequency value to each sounder amplitude scan line.

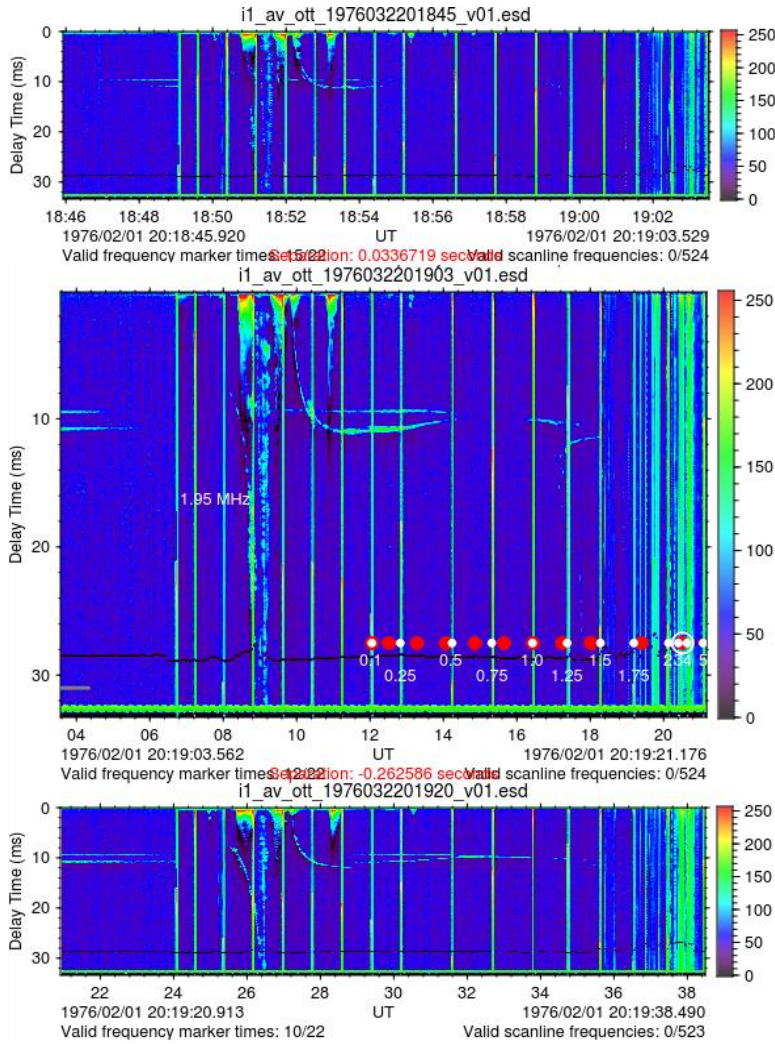
In order to detect timing-overlap problems, i.e., when an ionogram starts prior to the end of the previous ionogram, ionogram time spans are plotted on UT-altitude plots. Neighboring ionograms with large overlaps can then be visually identified easily with the help of efficient survey software developed for this purpose. Careful examination of these overlaps is conducted and those ionograms causing the overlaps may be removed to make sure the final ionograms are as complete as possible and are free from any large overlaps.

Many ionograms have frame-sync detection problems. As a result, one ionogram can be split into multiple ionograms and there can be multiple ionograms in one ionogram file. To fix this problem, we developed visual ionogram segmentation software to split/join ionograms appropriately so that each data file only has one unique ionogram. An example illustrating the problems to be corrected, and a display from the software developed to resolve the problem, is given in Figure 1.



**Figure 1.** An example of a version-1 ISIS-1 digital ionogram in need of correction because of incorrect segmentation, i.e., the proper ionogram frame sync pulse was not detected during the A/D process. Three consecutive version-1 ionogram files are displayed in this illustration of the software developed to address this problem.

An illustration of an ionogram after correcting the segmentation problem is given in Figure 2. Note that there are still problems with the frequency markers.

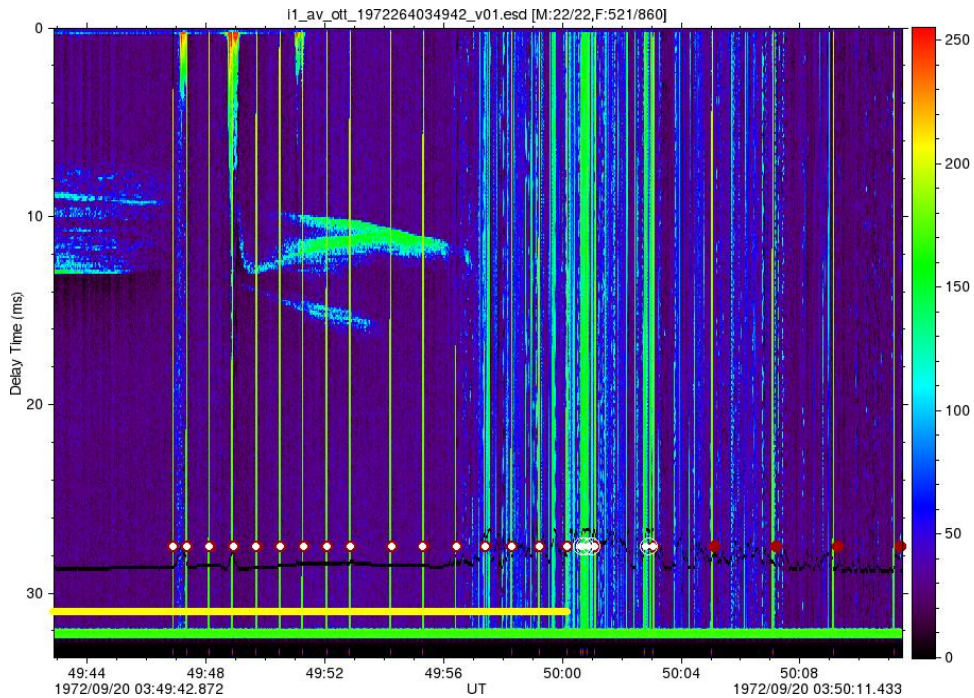


**Figure 2.** An example of a version-1 ISIS-1 digital ionogram with proper segmentation (middle panel) but in need of frequency-marker correction.

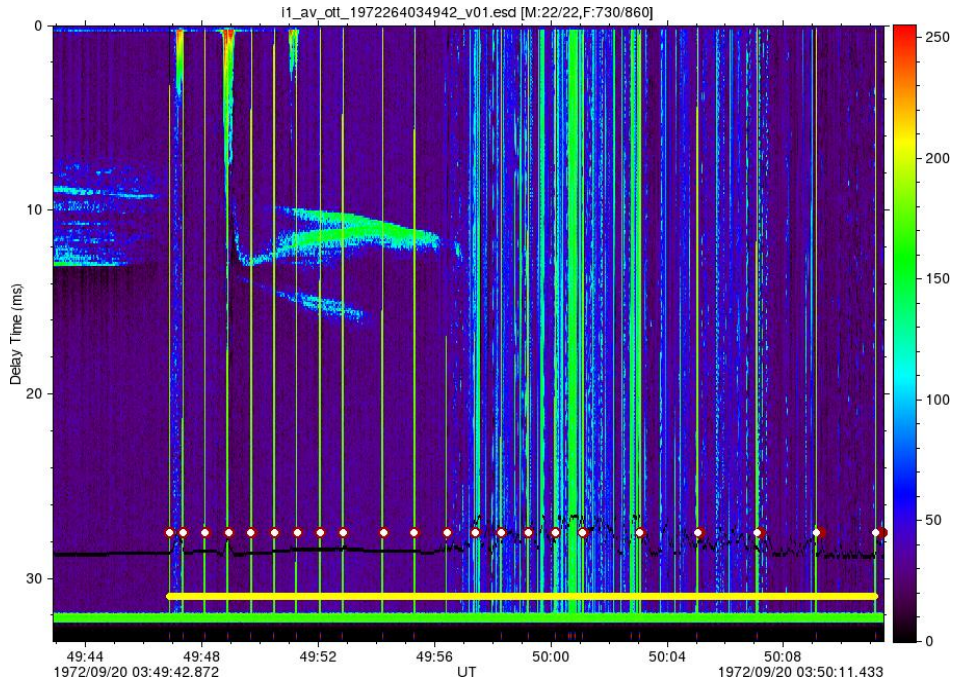
Even with version-1 ionograms with proper segmentation, there are often cases where ionogram frequency markers are missing or wrongly placed as illustrated in Figure 3. These markers have to be fixed to produce high-quality ionograms for scientific research. We developed efficient software for easy addition/deletion of markers. Standard markers are plotted as a background (red dots in Figure 3) that can be shifted relative to the current markers to provide a useful reference during marker correction. An automatic pattern-fitting program is used to automatically assign standard frequency values to the final markers.

There are five distinct frequency ranges: 0.1-2 MHz, 2-3 MHz, 3-5 MHz, 5-6 MHz, and 6-20 MHz. Frequencies falling outside of the time marker time ranges are set to negative values. Within each frequency range, we request at least two markers to allow effective frequency interpolation and frequencies outside of these markers will be set to

negative values. In the first, third, and fifth ranges, 3rd order polynomial interpolation is conducted when there are more than three markers, 2nd order polynomial interpolation is conducted when there are three markers, and linear interpolation is conducted when there are two markers. In the second and fourth ranges, linear interpolation is conducted when there are two markers at least. In addition, in the second range, an extra linear mapping: (2.0,2.0), (2.165,2.1), (2.39,2.3), (2.75,2.7), (3.0,3.0) is conducted, and in the fourth range, an extra linear mapping: (5.0,5.0), (5.52,5.5), (6.0,6.0) is conducted to account for special instrument adjustment as described in connection with Table A2 of *Benson and Bilitza* [2009]. Such an adjustment is not incorporated in the Version 1 ISIS 1 files, so each user application has to provide its own mapping. A corrected final version-2 ionogram is illustrated in Figure 4.



**Figure 3.** An example of a version-1 ISIS-1 digital ionogram in need of frequency-mark correction because of false frequency-marker detection due to interference. The red dots correspond to the expected location of the frequency markers based on a reference ionogram; the white dots correspond to the frequency markers detected during the A/D process.

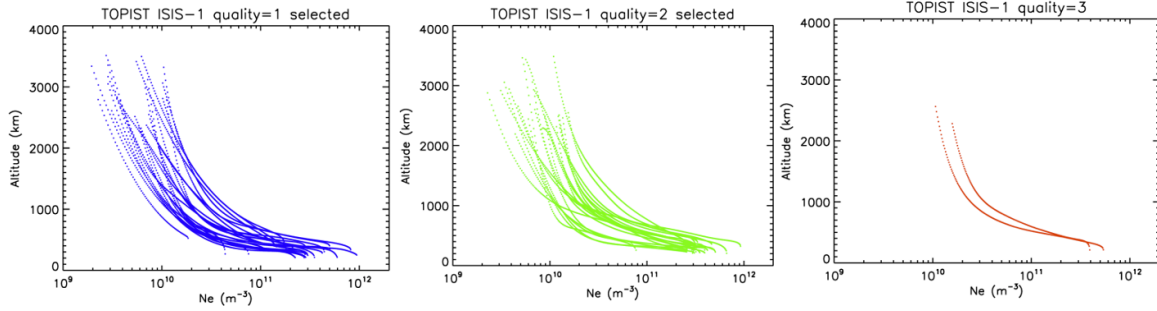


**Figure 4.** A software display of a final version-2 ISIS-1 digital topside ionogram with the yellow bar at the bottom indicating the range of correct frequency values.

The resulting version-2 ISIS-1 files will be suitable for the analysis of plasma-wave phenomena, as briefly reviewed in Section 3 of *Benson* [2010], and for the automatic processing of the ionogram reflection traces into  $N_e(h)$  profiles as illustrated in the next section.

#### 4. AUTOMATICALLY-PRODUCED $N_e(h)$ PROFILES

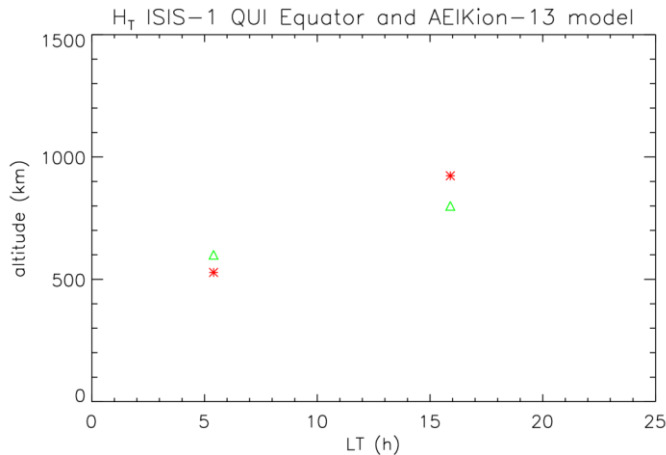
The number of digital ionograms available, as illustrated in Figure 2 of *Benson and Bilitza* [2009], calls for an automated analysis for the production of  $N_e(h)$  profiles. These profiles are of fundamental importance to improving the International Reference Ionosphere (IRI) and for the automatic determination of transition heights from  $O^+$  to  $H^+$ . The resulting version-2 ISIS-1 topside ionogram files produced during this project will be available from [spdf.gsfc.nasa.gov/isis/isis-status.html](http://spdf.gsfc.nasa.gov/isis/isis-status.html) and also from the Virtual Wave Observatory (VWO) [*Fung, 2010*]. As an illustration of the use of the version-2 ISIS-1 digital topside-ionogram files, all of the available version-1 files from the Quito telemetry station recorded during 1976 were processed through the TOPIST software. The resulting profiles, edited to remove files that appeared to have non-physical results, e.g., weird shape or the height of the F layer too low, are presented in Figure 5 corresponding to TOPIST-determined quality flags 1 (worst), 2 (medium), and 3 (best).



**Figure 5.** Left: 24 selected TOPIST-processed  $N_e(h)$  profiles with quality flag = 1, Middle: 22 selected TOPIST-processed  $N_e(h)$  profiles with quality flag = 2, Right: 2 TOPIST-processed  $N_e(h)$  profiles with quality flag = 3, from QUI during 1976.

One important application of such topside profiles is the determination of the upper transition height ( $H_t$ ); it corresponds to the altitude where the distribution of dominant ions changes from the topside ionosphere ( $O^+$ ) to the plasmasphere ( $H^+$  and  $He^+$ ). It is a key parameter since magnetospheric-ionospheric interaction processes are important in this transition region. We used a method developed by *Webb et al.* [2006] to determine  $H_t$ . This procedure assumes diffusive-equilibrium, uses an electron temperature model (IRI) as an input, and employs a least-square fit to  $N_e$  profiles to determine ion ( $O^+$  and  $H^+$ ) profiles and from them  $H_t$ .

A preliminary test using TOPIST ISIS-1 topside  $N_e(h)$  profiles from the equatorial telemetry station QUI was performed. We have selected only profiles from  $\pm 15^\circ$  diplat. Only two local times were populated (5.4 h and 15.9 h) by the data represented in Figure 5. The processed data show an average  $H_t$  of about 530 km for 5.4 h LT and about 920 km for 15.9 h LT. Solar activity was very low; the PF10.7 index was about 71. The AEIKion-13 model ([*Truhlik et al.*, 2015]) produced values of about 600 km and 800 km at these local times, respectively. Thus, there is a reasonable agreement between the data and the model as illustrated in Figure 6. The availability of more high-quality topside  $N_e(h)$  profiles will enable improvements to current models of  $H_t$ .



**Figure 6.** Local time dependence of the processed upper transition height (red \* - data, green  $\Delta$  - AEIKion-13 model)

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