Expanding the Topside Sounder Digital Data Collection

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ABSTRACT

The International Satellites for Ionospheric Studies (ISIS) program included four Canadian-built swept-frequency topside sounder satellites: Alouette 1 and 2, and ISIS 1 and 2. These satellites were launched between 1962 and 1971 and, together with other topside sounders, provided the first truly global maps of ionospheric density because they obtained observations over regions that were not readily accessible to ground-based instruments.

An effort has been underway for several years to preserve data from these satellites for modern analysis. A NASA effort has already transferred thousands of the original magnetic tapes to digital form. A pilot project is now underway to digitally preserve data stored on 35mm film using standardized file formats. This effort focusses on the ISIS-2 satellite, particularly on topside soundings made near Resolute Bay (74.7°N, 265.1°E). ISIS-2 had a polar circular orbit at 1400 km altitude, providing good coverage of the polar cap. Resolute Bay hosted both a ground station for acquiring ISIS-2 data, and a ground-based ionosonde, allowing complementary bottomside and topside soundings to be performed.

Periods of interest have been identified in which both topside and ground-based sounding data films exist. Software has already been developed to analyze film ionograms from ground-based sounders. New software is being developed to convert the topside film into digital ionograms with range and frequency information. Position information from the satellite ephemeris will also be added. Existing software such as TOPIST will be used to produce electron density profiles (EDPs) from the topside soundings for comparison with the ground-based EDPs. The storm-time behavior of the polar cap will be examined. Ultimately, the goal will be to compare polar cap profiles from this early 1970s data set with modern Resolute Bay observations.

1. INTRODUCTION

Since 1961, more than 30 satellites have been launched internationally with topside sounding capabilities. Between 1962 and 1971, four Canadian-built satellites carrying ionospheric sounders were launched as part of the International Satellites for Ionospheric Studies (ISIS): Alouette 1 and 2, and ISIS 1 and 2. These satellites were placed in polar orbits by NASA, giving good global coverage for mapping the ionospheric density above the F-region peak and studying in situ plasma resonances. The theory and operation of these topside sounders is discussed in detail in the special issue of *Proceedings of the IEEE*, June 1969 (Vol. 57 No. 6) devoted to topside sounding. Later reviews of topside sounder operations include *Jackson et al.* [1980] and *Benson* [2010].

This report focusses on ISIS-2 [*Daniels*, 1971], launched in 1971 and operational for 19 years. Data from the 1971-1973 period are examined specifically.

Satellite data were received by a network of more than 20 ground stations around the world and recorded on magnetic tape. Some of the magnetic tapes were then converted to 35 mm film for manual analysis, similar to the film ionograms produced by ground-based ionosondes of the era. Cost constraints limited the number of magnetic tapes that could be converted to film, and an even smaller number were analyzed in detail due to the complexity of producing electron density profiles and the limited computational resources available at the time. Thus *Benson and Bilitza* [2009] estimate that only about 177,000 of the millions of ISIS film ionograms had detailed EDP analyses.

Long-term ionospheric observations covering multiple solar cycles are rare. Such data sets are very valuable for studying global change, solar cycle variations, and infrequent space weather events that may elude campaign studies. *Rice et al.* [2014] described the use of modern methods to analyze film archives of ground-based ionosondes extending back to the 1940s, and one such historical data set from the early 1950s was compared to IRI by *Rice and Sojka* [2015]. The topside ionogram archive, extending back to 1961, is another unique resource for long-term studies.

A project was initiated by the NASA Ionosphere, Thermosphere, Mesosphere (ITM) Data Evaluation Panel to restore and preserve the topside ionogram archive. *Benson* [1996] worked to recover data from the original seven-track analog magnetic tapes and save them in modern digital form. Priority was given to tapes that had not been converted to film ionograms. Recovered data sets are available through the NASA Space Physics Data Facility web site (http://spdf.gsfc.nasa.gov/isis/isis-status.html) and the NASA Virtual Wave Observatory (http://vwo.gsfc.nasa.gov/). Recovering data from magnetic tape involved many technical challenges, but generally produced high-quality results.

The work described here is a complementary effort to recover the topside ionograms archived on film. The film ionograms have various limitations in the quality and type of information that can be obtained, compared to the magnetic tape, and the film digitization process can result in some loss of detail; there is also some added "noise" due to scratches and other flaws in the decades-old film reels. However, the basic procedure of recovering ground-based film ionograms has been worked out [*Rice et al.*, 2014], and modifying those procedures for topside film ionograms is the primary goal of the current project.

2. ISIS-2 FILM IONOGRAMS

The ISIS-2 data recorded on film is stored on 35 mm microfilm-size spools, rather than the large movie-style reels that many ground-based ionograms are archived on. The format makes these films easier to manage for review and digitization. Unfortunately, the collection of data films for the Alouette and ISIS satellites may not be retained indefinitely; their retention must be justified periodically. Digitizing the films is the only practical option for the long-term survival of this data set.

A typical film consists of images from a dozen or more magnetic tapes, each tape recording a pass of the satellite at a particular ground station. A header for each magnetic tape is recorded on the film, as shown in Figure 1. Film logs are available on microfiche which summarize the passes and modes on each film spool, but these are not in a machine-readable form.

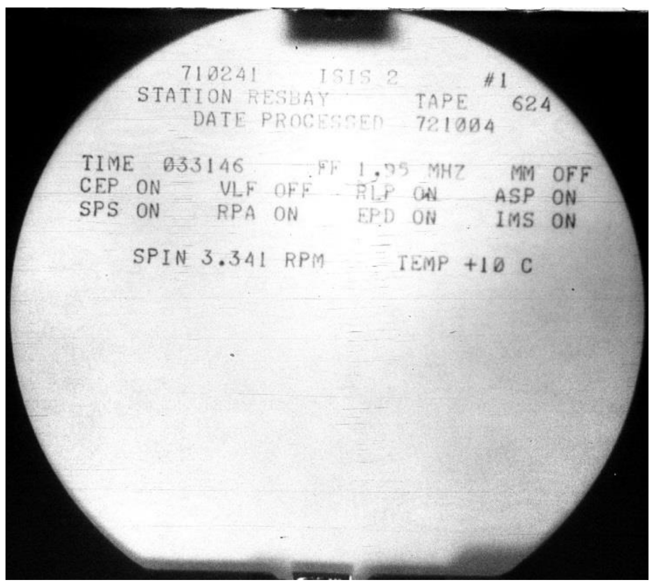

Figure 1. Magnetic tape header summarized on film. This pass was from 1972 day 173 (June 21), 0330-0336 UT, recorded at Resolute Bay.

The header information summarizes the state of instruments on the satellite, such as the VLF receiver (OFF in this case) and the retarding potential analyzer (RPA, ON in this case). This header indicates that the fixed-frequency sounding (FF) is made at 1.95 MHz, and that the mixed mode (MM) sounding option is OFF. The frames following the header may contain several types of information. For example, this ISIS-2 film contains receiver-only scans of HF bands, short sounding sweeps (0.1-10 MHz) and full sounding sweeps (0.1-20 MHz). The sounding sweeps typically begin with a fixed-frequency sounding (FF 1.95 MHz in this case). Thus parsing a digitized film is not trivial, and determining the frame boundaries and data types currently requires human interaction. In addition, the first few frames during acquisition of signal are often incomplete and may have incorrect time information, so fully-automated processing would require some intelligence to detect and discard faulty frames.

A full sounding frame is shown in Figure 2. The format is described by *Jackson* [1988]. The codes at the bottom of the frame identify the data source as ISIS-2 with 1.95 fixed frequency sounding (44), recorded at Resolute Bay (43), followed by the two-digit year, the day of year, the UT hour/minute, and the UT second. The white dots above these digits are 1-second markers; the timestamp refers to the marker above the first digit (4) of the code string. Thus the fixed-frequency sounding takes place from 03:33:19.2 to 03:33:22.3, and the swept-frequency sounding takes place from 03:33:22.3 to 03:33:41.5. Echoes returned from the ionospheric plasma below the sounder or from plasma resonances in the satellite's vicinity produce the dark features in the upper part of the frame. The light trace along the bottom of the frame is the automatic gain control (AGC) level, indicating the strength of the received background broadband noise.

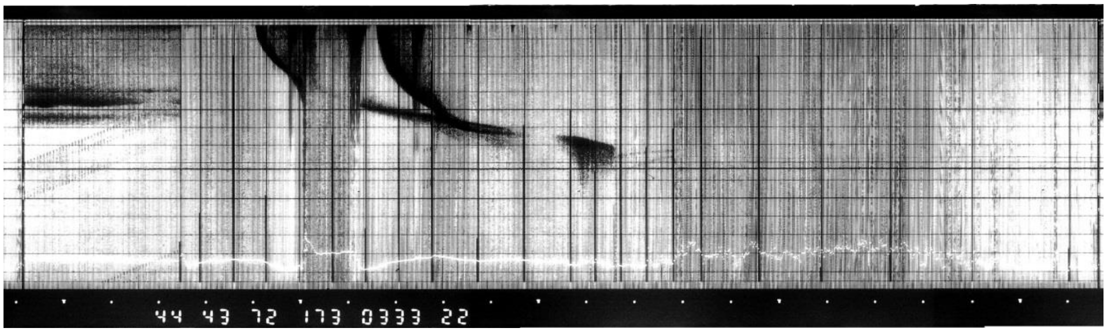

Figure 2. ISIS-2 full sounding sweep for 1972 day 173, starting at 03:33:22 UT. The 1.95 MHz fixed frequency sounding can be seen on the left, followed by the swept-frequency ionogram covering 0.1-20 MHz.

Figure 3 shows an enlargement of the swept frequency portion of the ionogram, with frequency, virtual range, and time notations added to the image. The virtual range markers are at 200 km intervals, but a special marker was inserted at 1668 km using a high-precision frequency source to allow the accuracy of the normal range markers to be checked.

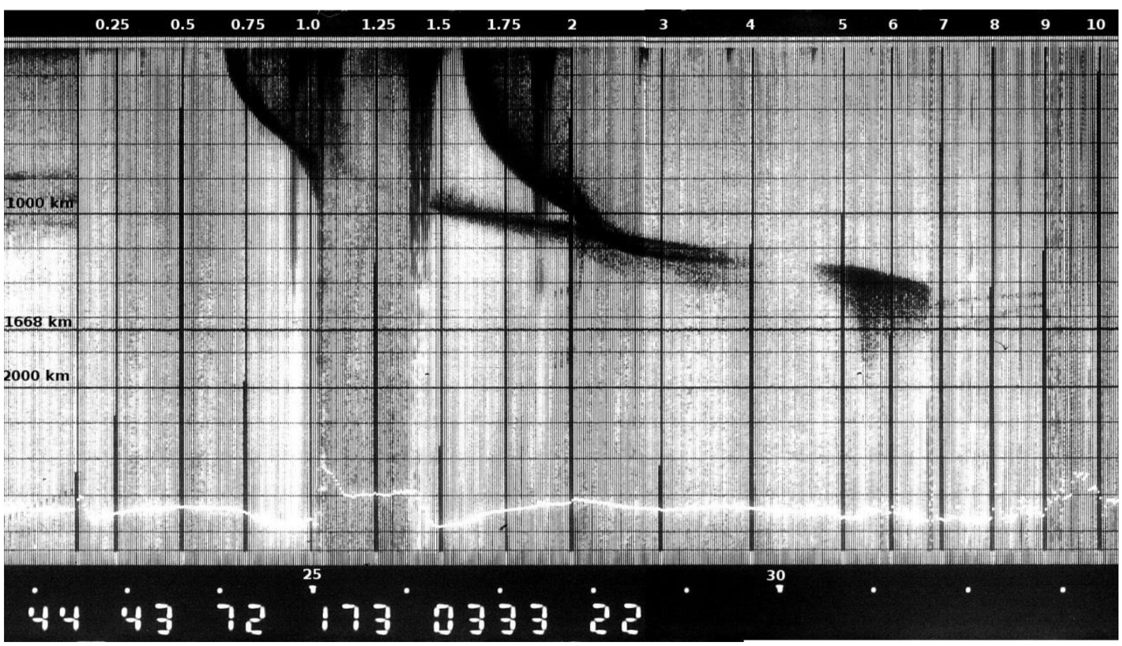

Figure 3. Enlarged section of Figure 2 showing the F-region topside traces. The frequency scale (MHz) is noted along the top edge, and the virtual distance is noted on the left side. The time ticks for 25 and 30 seconds are also marked.

The ISIS-2 satellite orbit was nearly circular (1423x1356 km). The virtual range of the F-region cusps are well below the true range of the Earth surface due to ionospheric retardation. An inversion process is needed to convert the virtual range into true range, and this process has been outlined by

Jackson [1969] and implemented in the TOPIST software [*Huang et al.*, 2002; *Bilitza et al.*, 2004; *Benson et al.*, 2012]. Other artifacts are peculiar to the topside sounding platform; the various spikes between 0.75-2 MHz are plasma resonances excited by the satellite transmitter, with smaller spikes above 2 MHz due mainly to harmonics of the electron-cyclotron frequency. Gaps in the trace, such as the 4-5 MHz gap, are due to the rotation of the satellite antenna system during the sounding and the transition between antennas used for the shorter and longer sounding wavelengths.

The satellite path for the entire Figure 2 frame (03:33:19-03:33:42 UT) is shown in Figure 4 relative to the Resolute Bay ground station and ionosonde. Two additional soundings occurred within 500 km of the Resolute Bay ionosonde RB974 during that northbound ISIS-2 pass.

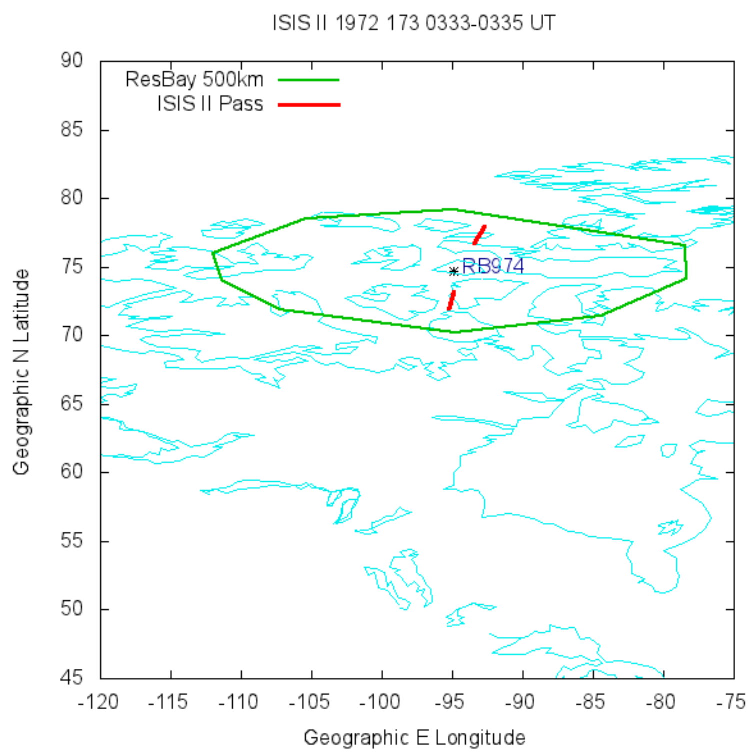

Figure 4. ISIS-2 soundings relative to Resolute Bay ionosonde (RB974). The 0333 UT sounding is shown by the red segment south of RB974. A second sounding at 0334 UT occurs nearly over the site (segment omitted for clarity), and a third sounding at 0335 UT is shown by the red segment north of RB974.

3. RESOLUTE BAY FILM IONOGRAMS

During the early 1970s, the Resolute Bay ionosonde RB974 (74.7°N, 265.1°E) recorded its data directly on 35 mm film. Archived film for this site was stored in the same microfilm spool format as the ISIS-2 ionograms, making it convenient to view and scan these ionograms. It would be possible to apply Space Environment Corporation's Expert System for Ionogram Reduction (ESIR) to these ionograms, as described for older film ionograms by *Rice et al.* [2014], and that may be attempted later for selected periods.

A review of the ionograms for the period of interest showed that many of the ionograms lack recognizable traces. The log sheets for this ionosonde are not currently available, so the only clues available are the notations on the hourly hand-scaled values available through NGDC SPIDR. Based on these notations, some of the nearly blank ionograms are due to ionospheric absorption, perhaps solar x-ray flares or polar cap absorption (PCA) events. A large number of the blank ionograms were flagged as "non-ionospheric" causes and might have been due to equipment problems; however, there seemed to be a correlation between these occurrences and ISIS-2 passes, leading to the suspicion that the RB974 transmitter might have been turned off intentionally during some ISIS-2 passes. While it seems unlikely that the ground-based ionosonde would have caused problems for the topside sounder, it is possible that its high-power pulses might have produced interference with the sensitive ground station equipment and therefore the transmitter was switched off during some satellite communications windows. Whatever the cause, fewer useful ground-based ionograms have been identified for ISIS-2 passes than anticipated.

The time period for the topside soundings shown in Figure 4 was one where ground-based ionograms were adequate. The Resolute Bay ionosonde was operating at the standard 15-minute cadence, so its closest ionogram in the period of interest was at 0330 UT (June 20, 2130 local time), shown in Figure 5. This ionogram represents the plasma frequencies of the ionospheric bottomside up to the F region peak. The normal E layer is seen to be partially obscured by a sporadic E layer at 100 km extending to 3 MHz. An F_1 layer is seen at about 250 km (virtual height), with f_oF_1 at about 4.3 MHz. These layers cannot be seen by the topside sounder. The F_2 layer is seen to exhibit moderate spread F, with f_oF_2/f_xF_2 in the 5.5-6.5 MHz range.

Comparing Figure 5 to the topside ionogram in Figure 3, spread can be seen in the topside F region, from the F_2 peak to the satellite altitude of about 1400 km. *Calvert and Schmid* [1964] showed that such high-latitude topside spread F was consistent with models of thin field-aligned structures. The f_oF_2/f_xF_2 frequency spread above the 1668 km marker is in the 5.5-6.5 MHz range, similar to the RB974 ionogram.

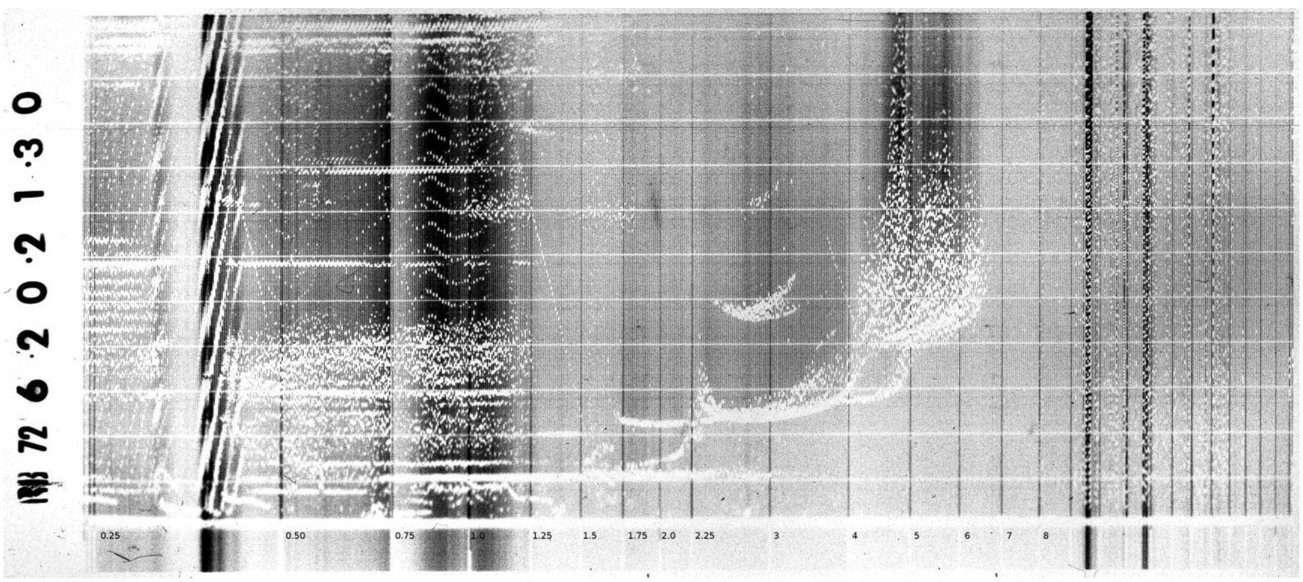

Figure 5. Resolute Bay ionogram taken just before the ISIS-2 pass. The ionogram frequency range was from 0.25-20 MHz and is indicated along the lower border of the image. Virtual height markers are at 100 km intervals.

4. EXPANDING THE DIGITAL TOPSIDE DATA ARCHIVE

Converting the 35 mm topside ionograms into digital form requires several steps of varying difficulty.

1. Scanning the film. The examples shown here were captured with manual microfilm scanners, which is very time-consuming. Bulk conversion of the entire 35 mm reel into a digital “ribbon file” is the next level to be attempted.
2. Identifying and storing individual frames. The scanned images do not correspond to individual frames. The manual scanner cannot capture a full frame in one image, so the frame (e.g., Figure 2) must be assembled from two or three smaller images. The bulk conversion ribbon file must be sliced into segments corresponding to the individual frames.

Identifying the frame boundaries is not easy to do automatically, and relies on several cues such as the black separator and the timestamp location.

3. Capturing time and coordinate metadata. The topside ionograms must be annotated with the full date and time obtained from optical character recognition of the timestamp on the image and the 1-second marker dots. The virtual range can be obtained fairly easily from the horizontal markers, with some additional quality/uncertainty information available from comparison of the 200 km markers with the 1668 km reference marker. The vertical frequency markers are slightly more difficult to identify, since they are sometimes masked by noise and sounding features, but their regular spacing allows the location of obscured markers to be inferred. In addition to these basic quantities, the satellite position can be calculated from the date and time information and added to the metadata.
4. Saving data in standardized formats. Some image formats allow the metadata to be saved with the image, providing digital ionograms that can be easily viewed by users; however, performing any sort of detailed analysis on the images is difficult, even with the metadata. The digital data will thus be saved in other formats, such as the Common Data Format (CDF) used by NASA. CDF will allow the ionogram to be treated as an array of signal strengths, and various analyses can then be performed on the data array.
5. Inverting the ionogram to obtain a true height electron density profile (EDP). Not all ionograms are suitable for inversion, but those that are can be processed once they are in a form such as CDF that includes full coordinate registration information. The EDP can be stored as a separate data object or included in the CDF as additional data.

These steps are currently being evaluated to determine the feasibility of automating some or all of the steps. It is hoped that steps 1-4 can be largely automated with a manual quality check of the frame identification in step 2 to allow incorrect identification or incomplete frames to be caught and dealt with. The inversion step would not be attempted routinely until the results of steps 1-4 can be performed with some confidence.

5. CONCLUSIONS

The development of a cost-effective means of converting archived topside ionogram films into digital images with coordinate registration and other metadata is crucial to the long-term survival of these unique ionospheric data sets. The films from the ISIS satellite series will be kept until 2017 by the Canadian Space Agency but retention beyond that point is subject to review. A practical plan for data conversion would help justify the continued existence of the film archive.

Data from the Resolute Bay area are of interest since the combination of topside and ground-based ionograms would provide full ionospheric profiles over a period of many years, even if close synchronization between the two soundings is not always possible. These profiles could be compared to current Resolute Bay incoherent scatter radar observations to study long-term trends and polar cap space weather phenomena.

On a broader scale, the topside sounding data are useful for checking and improving modern ionospheric models, since these observations are the only truly global measurements of the ionospheric topside that are available. Investigations of large-scale atmospheric waves (gravity, tidal, and planetary) can also be carried out using bottomside observations from the era together with modern wave models.

These and many other potential studies could be carried out with this unique data set if it can be preserved and converted to digital format. Making the digitized observations available to all researchers via the internet would create many new research opportunities.

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