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New Data on the Topside Electron Density Distribution

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Abstract. The existing uncertainties about the electron density profiles in the topside ionosphere, i.e., in the height region from hmF2 to ~2000 km, require the search for new data sources. The ISIS and Alouette topside sounder satellites from the sixties to the eighties recorded millions of ionograms and most were not analyzed in terms of electron density profiles. In recent years an effort started to digitize the analog recordings to prepare the ionograms for computerized analysis. As of November 2001 about 350,000 ionograms have been digitized from the original 7-track analog tapes. These data are available in binary and CDF format from the anonymous ftp site of the National Space Science Data Center. A search site and browse capabilities on CDAWeb assist the scientific usage of these data. All information and access links can be found at http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html. This paper describes the ISIS data restoration effort and shows how the digital ionograms are automatically processed into electron density profiles from satellite orbit altitude (1400 km for ISIS-2) down to the F peak. Because of the large volume of data an automated processing algorithm is imperative. The automatic topside ionogram scaler with true height algorithm TOPIST software developed for this task is successfully scaling ~70 % of the ionograms. An 'editing process' is available to manually scale the more difficult ionograms. The automated processing of the digitized ISIS ionograms is now underway, producing a much-needed database of topside electron density profiles for ionospheric modeling covering more than one solar cycle. The ISIS data restoration efforts are supported through NASA's Applied Systems and Information Research Program.

Introduction

Modeling of the topside ionosphere (from F peak to about 2000 km) suffers from a scarcity of data because ground-based ionosondes only probe up to the F-peak. Satellite-borne sounders provided information about the topside ionosphere. But only a small percentage of these data have been processed into electron density profiles, which is the parameter of greatest interest for topside modeling.

An ionosonde transmits signals sweeping through a typical frequency range and records the time delay it takes the signal to be reflected back to the receiver. The ionogram established in this way usually consists of an ordinary and extraordinary trace (O- and X-trace). Ionogram analysis consists of finding these traces and then inverting them into an electron density profile. The problem of the topside sounder missions in the sixties and seventies and the reason for the low percentage of obtained electron density profiles is the fact that the scaling had to be done manually. In the eighties and nineties, automated scaling and inversion algorithms were developed and perfected [Huang and Reinisch, 1983] and are now well-established tools of space weather observations with ground-based ionosondes [Reinisch et al., 2001]. This paper describes an effort to apply these automated scaling and inversion routines to the large database established by the US/Canadian Alouette and ISIS topside sounders.

The Alouette-1, -2 and ISIS-1, -2 satellites were the first satellites that were equipped with topside sounder instruments to monitor the topside ionosphere from the satellite orbit altitude down to the F-peak. The launch dates and orbit parameters are listed in Table 1. ISIS 1 launched in 1969 and ISIS 2 launched in 1971 were operated by NASA until 1979, then by CRC (Canada) until 1984, and finally by RRL (Japan) until 1990. Additional instruments carried by these satellites included VLF-receivers, Energetic

Particle Detectors (EPD), Ion Mass Spectrometers (IMS), Retarding Potential Analyzers (RPA) and Photometers. These satellites either had limited onboard recording capabilities (ISIS) or none at all (Alouette). Data were therefore primarily recorded within the viewing area of several telemetry downlink stations. Because of the great interest in these data many nations participated in the Alouette/ISIS program and provided dedicated telemetry stations (Table 2). Of the close to a million ionograms recorded by the Alouette/ISIS satellites several tens of percent are stored on more than 12,000 rolls of 35 mm microfilm at the National Space Science Data Center (NSSDC). Only a few percent of the ionograms were processed into electron density profiles. About 150,000 profiles were submitted to NSSDC's archives and are now available online from NSSDC's anonymous ftp site at ftp://nssdcftp.gsfc.nasa.gov/.

TABLE 1. Orbit Parameters

Satellite	Launch Date	Height Range /km	Inclination/degree
Alouette 1	1962-09-29	1000	80
Alouette 2	1965-11-29	500-3000	80
ISIS 1	1969-01-03	550-3500	88
ISIS 2	1971-04-01	1400	88

TABLE 2. The 24 ground stations for which tapes were selected; for each of the four satellites the number of tapes is shown and in brackets the years covered.

Location	*Station ID*	*Lat.*	*Long.*	*Al-1*	*Al-2*	*ISIS-1*	*ISIS-2*
Resolute Bay, Canada	RES	75	265			327 (76)	504 (73-79)
Tromso, Norway	TRO,TRM	70	19			320	141 (73-76)
Sodankyla, Finland	SOD	67	27				63 (77-79)
Fairbanks, Alaska	ULA	65	212	1(62)		244 (73-79)	439 (73-79)
Winkfield, U.K.	WNK	51	359		2(66)	319	405 (73-79)
Ottawa, Canada	OTT	45	284			1187 (69-83)	991 (73-83)
Kashima, Japan	KSH	36	141			103 (78-81)	879 (73-79)
Las Palmas Canary Island, Spain	CAN	28	345				106 (74-75)
Ahmedabad, India	AME	23	73				265 (73-77)
Ouagadougou, Burkina Faso	ODG	14	359			745 (73-?)	214 (73-75)
Kwajalein, Marshall Islands	KWA	9	168				140
Kourou, French Guyana	KRU	5	307				212 (74-77)
Quito, Equador	QUI	-1	281	1(62)	700	483 (69-72)	366 (73-79)
Brazzaville, Congo	BRZ,BZV	-4	15				34 (73-74)
Ascension Island, U.K.	CAN	-8	346				174 (75-77)
Lima, Peru	LIM	-12	283		11		
Johannesburg, South Africa	BUR,JOB	-26	28				192 (73-75)
Santiago, Chile	SNT,AGO	-33	298		428	209 (69)	240 (73-76)
Orroral, Australia	ORR	-36	149			66 (72-?)	232 (723-78)
Lauder, New Zealand	LAU	-45	170				604 (73-80)
Kerguelen Islands, France	KER	-49	70			98 (81-83)	464 (77-83)
Falkland Island, U.K.	SOL	-52	302		421		45 (72)
Terre Adelie, Antarctica	ADL	-67	140			54 (82-83)	738 (73-83)
Syowa Base, Antarctica	SYO	-69	40				241 (78-82)

This is also the story of a successful data restoration effort that saved a considerable portion of an irreplaceable dataset from the brink of extermination. The Alouette and ISIS telemetry data were stored on more than 100,000 7-track tapes in the Canadian Public Archives (CPA). In the early nineties the CPA indicated its intent to discard these tapes because of storage space and cost limitations and the dormant state of these data. With help from G. James (CRC, Ottawa) and with funding from NASA/OSS/AISRP,

R. Benson managed to save about 18,000 of these tapes (specifically selected for time and location; see next section) and ship about 14,000 to the Goddard Space Flight Center (GSFC) for processing and analysis. The rest of the telemetry tapes was discarded and the information contained on them is now lost.

Digitization of ISIS ionograms

At GSFC the analog topside sounder recordings from the 7-track tapes were digitized and made available online through NSSDC's anonymous ftp archive. Before this, however, the important first step in this data restoration effort was the selection of desirable tapes, because it became clear that it was feasible to only save about 10-20% of the tape total. The tapes were selected in order to obtain global coverage and to accommodate special requests that address subjects and time periods of particular interest. The selection included data from 24 telemetry stations from the years 1972 – 1984. Table 2 provides some of the specifics in terms of the number of tapes from a specific satellite and stations and the years covered. In selecting these tapes we also considered the time periods already covered by NSSDC's data holdings. Typically, 80-100 tapes/year were specified centered on each of the equinoxes and solstices. About 8,000 tapes were selected with special emphasis on time periods coinciding with the DE satellites and from stations close to the magnetic equator, an area not so well covered by the existing datasets.

The digitization at GSFC's Data Evaluation Laboratory (DEL) was performed using an A/D converter board and software device driver compatible with the OS/2 operating system used by a 486-based Programmable Telemetry Processor (PTP). The digitized sounder data consist of 8-bit receiver-amplitude values collected at a 40 kHz rate and contain the time and the frequency associated with each sounder pulse. The data are provided in full and average (4 consecutive range bins averaged to yield one amplitude sample) in OS2 binary format; the average resolution data were also converted to CDF format at NSSDC. The virtual range resolution is 3.75 km for the full resolution ionograms and 15 km for the average resolution data. As of November 2001 about 350,000 ionograms have been digitized. A small selection of these data has also been made available for plotting and browsing on CDAWeb (http://cdaweb.gsfc.nasa.gov/). Other services available from the ISIS homepage include a search page for locating ionograms for specific times, locations, and other search criteria and software for an interactive IDL interface for plotting, scaling, and inverting the ionograms based on the inversion program of Jackson [1969].

Automatic Profiles with TOPIST

Our goal was to automatically deduce the electron density profiles from the digitized ionograms. This is the logical next step after the digitization process since topside electron densities are one of the most important data products derived from ionograms. This requires locating and identifying the echo traces on the ionogram and then applying an inversion algorithm that inverts the echo traces into an electron density profile. Because of the large volume of ionograms this has to be done automatically in order to provide the maximum input to ionospheric models. A TOPside Ionogram Scaler with True height algorithm (TOPIST) program has been developed that is successfully scaling ~70 % of the ionograms. The TOPIST software also includes an "editing option" (called Manual Scaling in Figure 1) for the manual scaling of the more difficult ionograms, which could not be scaled during the automated TOPIST run.

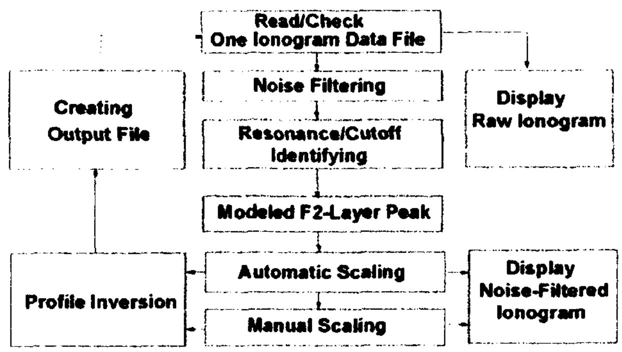

Figure 1. Flow chart of TOPIST

The most difficult part of the task is the automatic scaling of the echo traces. Unlike the ionograms from modern ionosondes [Reinisch, 1996] the ISIS ionograms do not identify the wave polarization of the different echo traces, so physical logic must be applied to identify the O and/or X traces, and this, of course, is not always successful. Characteristic resonance features seen in the topside ionograms include those at the gyro and plasma frequencies. An elaborate scheme was developed to automatically identify these resonance frequencies in order to determine the local plasma and gyro frequencies. This information helps in the identification of the O and X traces, and it provides the starting density of the electron density profile. The inversion of the echo traces into electron density profiles uses the same modified Chebyshev polynomial fitting technique that has been successfully applied in the analysis of topside ionograms and ground-based Digisonde ionograms [Huang and Reinisch, 1982; Reinisch and Huang, 1983].

Processing Procedures

The flowchart in Figure 1 and Table 3 describe the individual steps that TOPIST takes to analyze the ionograms. The performance characteristics of TOPIST are summarized in Table 4.

Table 3. Processing functions in TOPIST

Process	Method
Reading ionogram file	Full or average ionogram/OS2 binary
Noise Filter	Individual threshold for each frequency. Most probable amplitude at low ranges and at large ranges is determined. Smaller value is selected as nominal threshold
Search for resonance frequencies	5-frequency comb with f_N as free variable slides along frequency axis in search for maximum amplitude
Consult model F2 peak parameters	FoF2 and hmF2 values are calculated from URSI and CCIR coefficients and used as guide for the auto-scaling. If ground echo traces are observed, they also are used in the foF2 search.
Trace scaling	Find potential trace points for each frequency line storing their amplitude and connection length to neighbors. Find optimal combination of resonance frequencies and O- and X-traces using a family of generic functions
Electron density profile calculation	Introduce a reduced frequency variable and represent profile with Chebyshev polynomials. Inversion can work with O-trace only, or X-trace only, or both traces and possibly the Z-trace

Table 4. TOPIST Performance

Function	Description
Test database	~800 digitized ISIS-2 ionograms
Success rate	70% of manually scalable ionograms are successfully auto-scaled
Auto-scaling failures	Scaling errors occur during severe spread; when data are missing in a large frequency interval; in the presence of unidentified traces (oblique?); when resonance frequencies are incorrectly identified

Figure 2 is an example of a digital ISIS-2 ionogram that has been processed by TOPIST: the background noise has been reduced, and the O- and X traces as well as the resonance and cutoff frequencies have been identified. The heavy black line is the plasma frequency profile calculated from the autoscaled traces. TOPIST also recalculates the expected O-, X-, and Z-traces using the profile and the resonance frequencies and superimposes them on the ionogram. The tight agreement of these recalculated traces with the observed traces verifies the correctness of the profile.

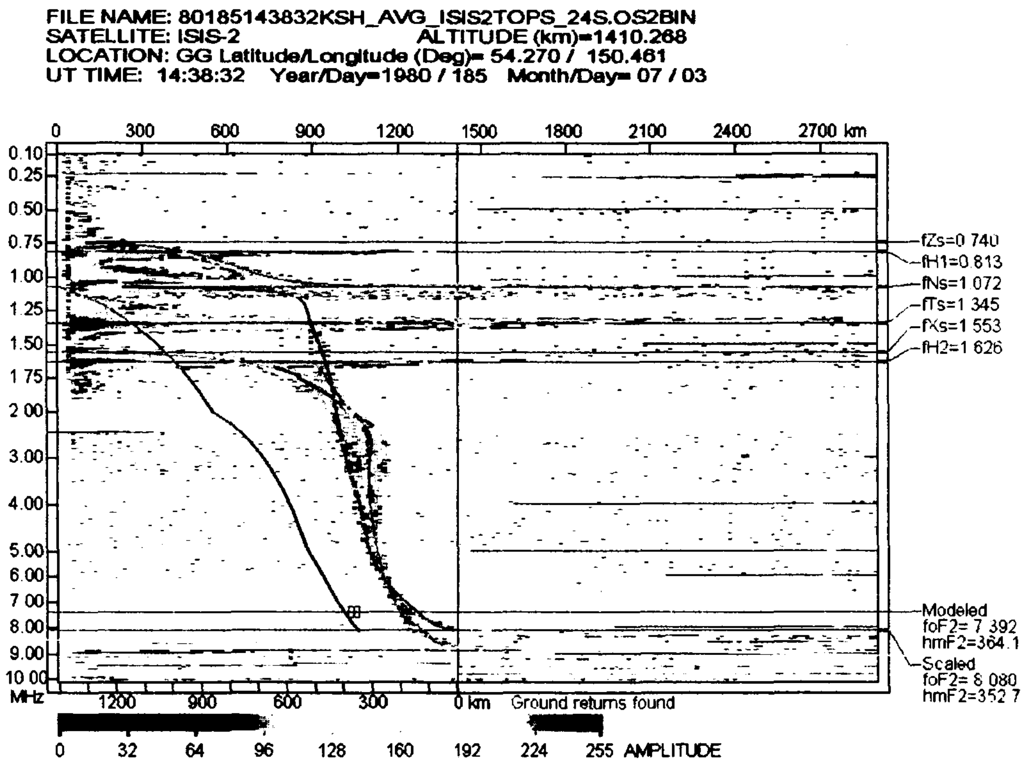

Figure 2. The autoscaled ISIS-2 ionogram gives the electron density profile, the resonance and cutoff frequencies, and confirms the scaling accuracy by superimposing the recalculated O-, X-, and Z-traces.

Summary and Discussion

A considerable amount of a very valuable data source for the topside ionosphere has been saved in a last minute effort. Close to 340,000 topside ionograms have so far been digitized and this process continues at a rate of about 6000 per month. A software algorithm (TOPIST) was developed for automated scaling and inversion of ionograms and is now successfully scaling about 70% of the digitized ionograms. The resulting topside electron density profiles are being made available online from NSSDC's anonymous ftp archive (nssdcftp.gsfc.nasa.gov).

This unique new data source for modeling the topside electron density will more than triple the amount of electron density data previously available from the Alouette and ISIS satellites, and it will greatly extend the solar cycle coverage of the combined Alouette/ISIS database. A better representation of conditions during very high solar activity is especially important because the largest topside electron densities are found during these time periods and, as a result, the strongest space weather effects occur during such intervals. For real time space weather monitoring future topside sounders should provide for automatic scaling of the ionograms as proposed by Reinisch et al. [2001].

The data set will also help special investigation that were considered in selecting the original telemetry tapes, e.g., combining ISIS data with coincident DE data, the investigation of sounder-stimulated plasma resonances, and studies of high latitude and low latitude plasma processes. Benson and Grebowsky [2001] have recently demonstrated the importance of these new digital data. They produced several orbit-plane electron-density contours, based on manual scaling using the analysis program available from the NSSDC, through the winter, nighttime polar cap ionosphere during solar minimum. Their observations, combined with other data, suggest that an absence of an F-layer ionization peak may be a frequent occurrence at high latitudes.

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