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Topside Ionogram Scaler With True Height Algorithm (TOPIST): Automated processing of ISIS topside ionograms

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[1] The United States/Canadian ISIS-1 and ISIS-2 satellites collected several million topside ionograms in the 1960s and 1970s with a multinational network of ground stations that provided good global coverage. However, processing of these ionograms into electron density profiles required time-consuming manual scaling of the traces from the analog ionograms, and as a result, only a few percent of the ionograms had been processed into electron density profiles. In recent years an effort began to digitize the analog recordings to prepare the ionograms for computerized analysis. As of November 2002, approximately 390,000 ISIS-1 and ISIS-2 digital topside-sounder ionograms have been produced. The Topside Ionogram Scaler With True Height Algorithm (TOPIST) program was developed for the automated scaling of the echo traces and for the inversion of these traces into topside electron density profiles. The program is based on the techniques that have been successfully applied in the analysis of ground-based Digisonde ionograms. The TOPIST software also includes an "editing option" for manual scaling of the more difficult ionograms, which could not be scaled during the automated TOPIST run. TOPIST is now successfully scaling ∼60% of the ISIS ionograms, and the electron density profiles are available through the online archive of the National Space Science Data Center at ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/isis/topside_sounder. This data restoration effort is producing a unique global database of topside electron densities over more than one solar cycle, which will be of particular importance for improvements of topside ionosphere models, especially the International Reference Ionosphere. *INDEX TERMS:* 2481 Ionosphere: Topside ionosphere; 2447 Ionosphere: Modeling and forecasting; 2415 Ionosphere: Equatorial ionosphere; *KEYWORDS:* topside sounder, TOPIST, ionogram inversion, topside ionogram, ISIS

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1. Introduction

[2] Modeling of the topside ionosphere, i.e., the region from the F2 peak to about 2000 km, suffers from a scarcity of data because ground-based ionosondes only probe up to the *F* peak. Satelliteborne sounders provided information about the topside ionosphere. However, only a small percentage of these data have been processed into electron density profiles, which is the parameter of greatest interest for topside modeling.

[3] A topside ionosonde transmits signals sweeping through a typical frequency range from 0.1 to 10 or 20 MHz and records the time delay of the ionospheric echoes. The ionogram established in this way usually includes an ordinary and an extraordinary reflection trace (O and X trace). Ionogram analysis requires finding these traces and then inverting them into an electron density profile. The problem of the topside sounder missions in the 1960s and 1970s and the reason for the low percentage of electron density profiles obtained is that the scaling had to be done manually. In the 1980s and 1990s,

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Table 1. Alouette and ISIS Satellite Orbit Parameters

Satellite	Launch Date (yyyy-mm-dd)	Height Range, km	Inclination, deg
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

automated scaling and inversion algorithms were developed and perfected [*Huang and Reinisch*, 1982; *Reinisch and Huang*, 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 U.S./Canadian Alouette and ISIS topside sounders.

[4] The Alouette-1 and -2 and ISIS-1 and -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 the Canadian Research Council (CRC) until 1984, and finally by the Radio Research Laboratory (RRL) of Japan until 1990. The satellites carried additional instruments including VLF receivers, energetic particle detectors, ion mass spectrometers, retarding potential analyzers, and photometers. The ISIS satellites had limited onboard recording capabilities, and Alouette had none at all. 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 one 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 available online at ftp://nssdcftp.gsfc.nasa.gov/.

[5] This is also the story of a successful data restoration effort that saved a considerable portion of an irreplaceable data set 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 1990s 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 Office of Space Science(OSS) Applied Information Sys-

Table 2. The 24 Ground Stations for Which Tapes Were Selected[a]

Location	Station ID	Latitude	Longitude	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, UK	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, Ecuador	QUI	−1	281	1(62)	700	483 (69–72)	366 (73–79)
Brazzaville, Congo	BRZ,BZV	−4	15				34 (73–74)
Ascension Island, UK	ACN	−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, UK	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)

[a] For each of the four satellites the number of tapes is shown and in parentheses the years covered.

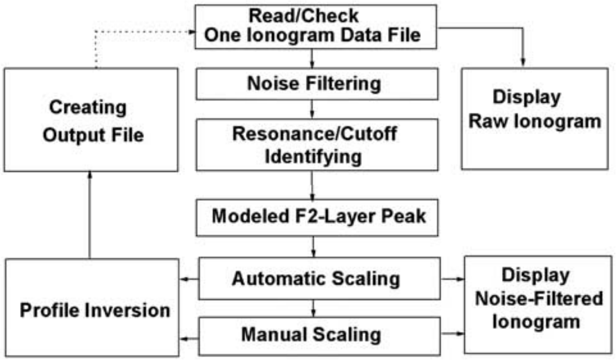

Figure 1. Flowchart of the TOPIST program.

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

2. Digitization of ISIS Ionograms

[6] At GSFC the analog topside sounder recordings from the 7-track tapes were digitized and submitted to NSSDC's online 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 years covered. These tape selection also considered the time periods already covered by NSSDC's data holdings. Typically, 80–100 tapes/year/station were specified, centered on each of the equinoxes and solstices. About 8000 tapes were selected with special emphasis on time periods coinciding with the Dynamics Explorer (DE) satellites and from stations close to the magnetic equator, an area not so well covered by the existing data sets.

[7] The digitization at GSFC's Data Evaluation Laboratory (DEL) was performed using an analog to digital (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 signal amplitude values collected at a 40 kHz rate and are supplemented by the time and the frequency associated with each sounder pulse. Full and average (four consecutive range bins averaged to yield one amplitude sample) are provided in OS/2 binary format. The virtual range resolution is 3.75 km for the full-resolution ionograms and 15 km for the average-resolution data. As of November 2002, about 390,000 ionograms have been digitized, and processing continues at a rate of about 7000 ionograms per month. A copy of the average-resolution data in common data format (CDF) is being made available for plotting and browsing on CDAWeb at http://cdaweb.gsfc.nasa.gov/. Other services available from the ISIS homepage at http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html include a search page for locating ionograms for specific times, locations, and other search criteria and interactive software for plotting, scaling, and inverting the ionograms based on the inversion program of *Jackson* [1969].

3. TOPIST Processing

[8] Deducing electron density profiles from the digitized ionograms requires locating and identifying the echo traces on the ionogram and then applying a mathematical 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 generate maximum data input for ionospheric modeling. The Topside Ionogram Scaler With True Height Algorithm (TOPIST) program was developed for this purpose.

[9] The most difficult part of the task was 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].

[10] The flowchart in Figure 1 illustrates the individual steps that TOPIST takes to analyze the ionograms, and Table 3 describes these steps in greater detail [see also *Huang et al.*, 2002]. Figure 2 is an

Table 3. Processing Functions in TOPIST

Process	Method
Reading data	full or average ionogram in OS/2 binary format
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	five-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 autoscaling 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

example of a digital ISIS-2 ionogram 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. TOPIST also finds the F2 peak plasma frequency foF2 and the peak height hmF2 and compares these with International Reference Ionosphere (IRI) model predictions as indicated in Figure 2.

[11] As of November 2002 the majority of the ISIS-2 ionograms have been processed by TOPIST with a success rate of about 60%, generating a database of ~120,000 new topside electron density profiles. The most common causes for TOPIST failures are: (1) severe spread that makes trace identification very difficult, (2) scaling errors due to missing trace data in a large frequency interval, (3) scaling errors in the presence of unidentified traces (oblique?), (4) incorrect identification of resonance frequencies, and (5) incomplete or corrupted ionogram files. 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. The final TOPIST output is stored in ASCII form using the internationally recommended IIWG format that is widely used in the ionosonde community.

4. Topside Modeling

[12] This new data source is of special benefit for modeling the electron density in the F2 peak region and topside ionosphere. Current empirical models are based on a small amount of data from the topside ionosphere and are accordingly limited in their accuracy especially in terms of predicting variations with solar cycle [e.g., *Bilitza and Williamson*, 2000]. The *Bent et al.* [1972] model, one of the earliest and still heavily used models, is based on a few years of Alouette 1 topside sounder data. The IRI topside model [*Rawer et al.*, 1978], the de facto international standard, is an analytical representation of the *Bent et al.* [1972] model with input from incoherent scatter radar data. Both of these important models are therefore based on only a small fraction of the empirical evidence collected by the Alouette/ISIS satellites. Our TOPIST project will more than triple the existing Alouette/ISIS database including new data from Alouette 2, ISIS-1, and ISIS-2. This data source is particularly valuable for topside modeling because modeling needs in terms of global, seasonal, and solar cycle coverage were an important driver behind the selection of tapes to be processed. Our data set will complement the data acquired in more recent years by the topside sounder instruments that were flown on the Japanese ISS-b satellite [*Matuura et al.*, 1981; *Iwamoto*, 1985] and on the Russian Intercosmos-19 satellite (http://antares.izmiran.rssi.ru/projects/IK19/) [*Pulinets et al.*, 2002].

[13] The limitations of the current IRI topside model are illustrated in Figure 3 with the help of Alouette 2 electron density data from NSSDC's archive (manually scaled profiles). The graph shows the ratio between sounder data and IRI model predictions versus altitude above the F2 peak during daytime (1000–1400 LT) using all Alouette 2 profiles (7147 total) available for this time period in the NSSDC data set. The IRI values were computed using the measured F2 peak density and height. In this way we eliminate the influence of the IRI peak parameter model on the topside profile and can evaluate discrepancies in the IRI specification of the topside profile shape. Figure 2 indicates that IRI slightly underestimates the

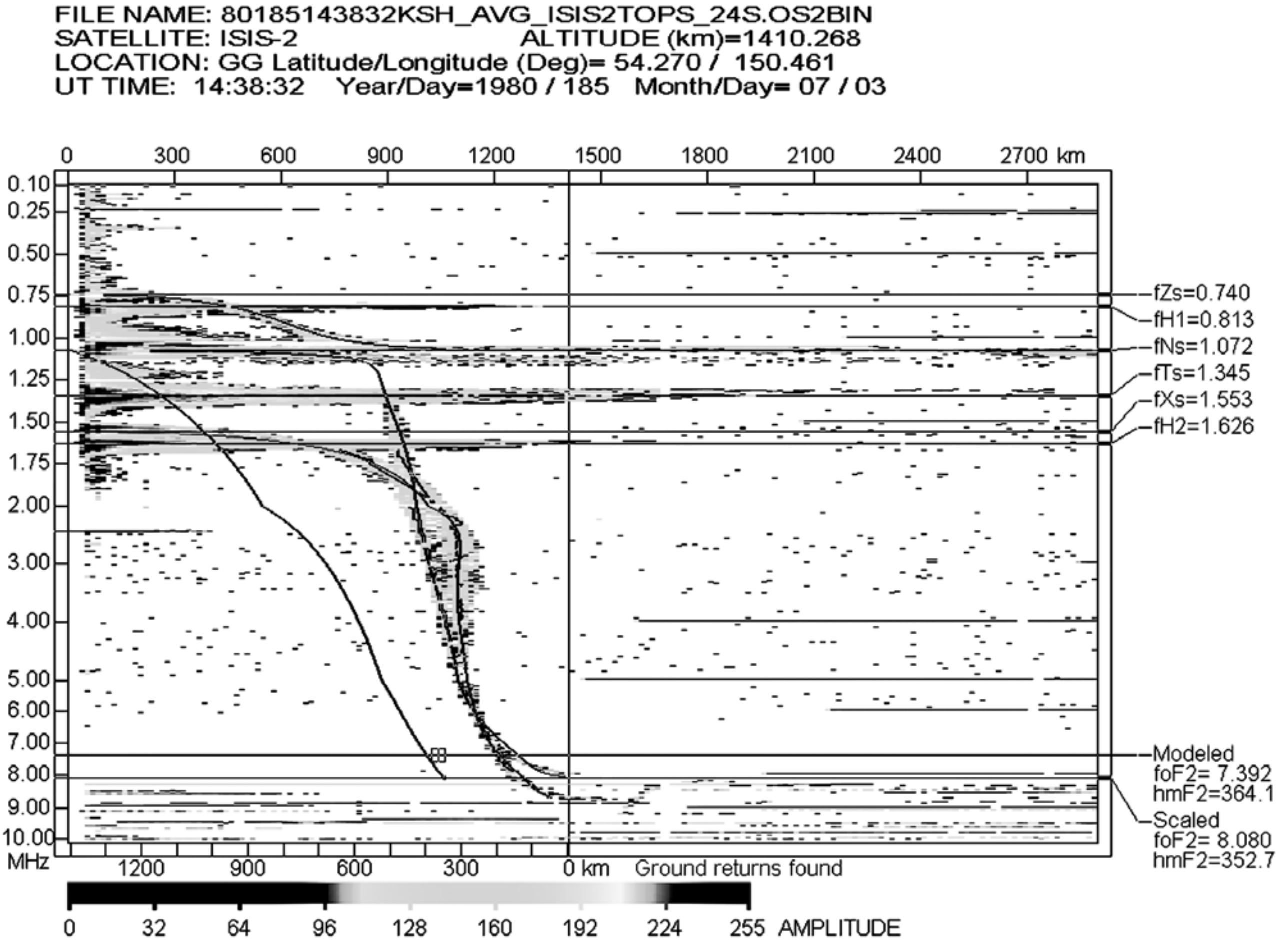

Figure 2. The autoscaled ISIS-2 ionogram gives the electron density profile, the resonance, and cutoff frequencies and confirms the scaling accuracy by superimposing the recalculated O, X, and Z traces. The uneven step size along the frequency axis produces apparent kinks in the profile curve. See color version of this figure at back of this issue.

electron density near the *F* peak and strongly overestimates densities in the upper topside. Efforts are now underway to use these comparisons to establish correction factors for IRI.

5. Summary

[14] A considerable amount of a very valuable data source for the topside ionosphere has been saved in a last minute effort. Close to 390,000 topside ionograms have been digitized as of November 2002, and this process continues at a rate of about 7000 per month. A new software algorithm, TOPIST, for the automated scaling and inversion of ionograms has a ~60% success rate in processing the digitized ISIS ionograms. The ionograms and resulting topside electron density profiles are available online from NSSDC’s anonymous ftp archive (http://nssdcftp.gsfc.nasa.gov).

[15] This unique new data source for modeling the topside electron density more than triples the amount of electron density data available from the Alouette and ISIS satellites and greatly extends 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].

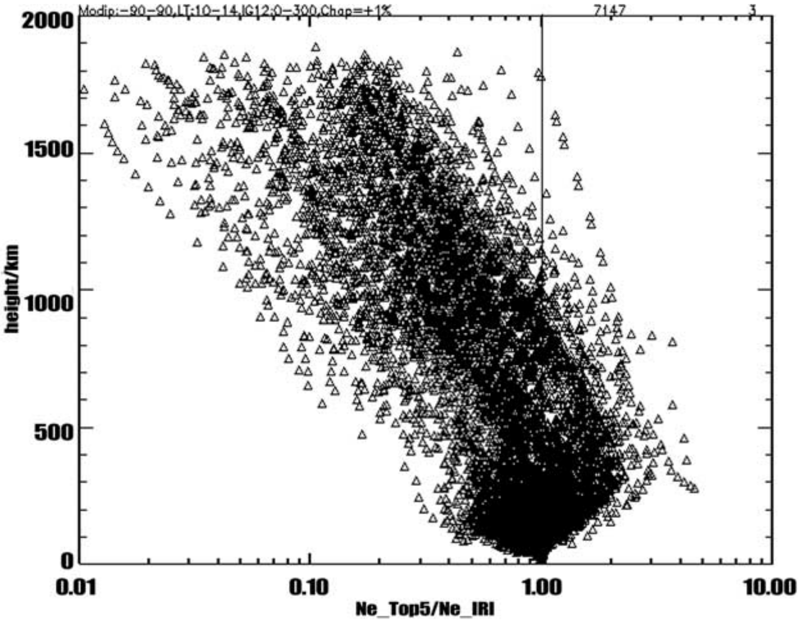

Figure 3. Ratio between topside sounder deduced densities (Ne_TopS) and densities predicted by the IRI model (Ne_IRI) during noontime (1000–1400 LT). Data and model values are normalized to the measured *F* peak density and height.

[16] 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 on the basis of manual scaling using the analysis program available from the NSSDC through the winter and 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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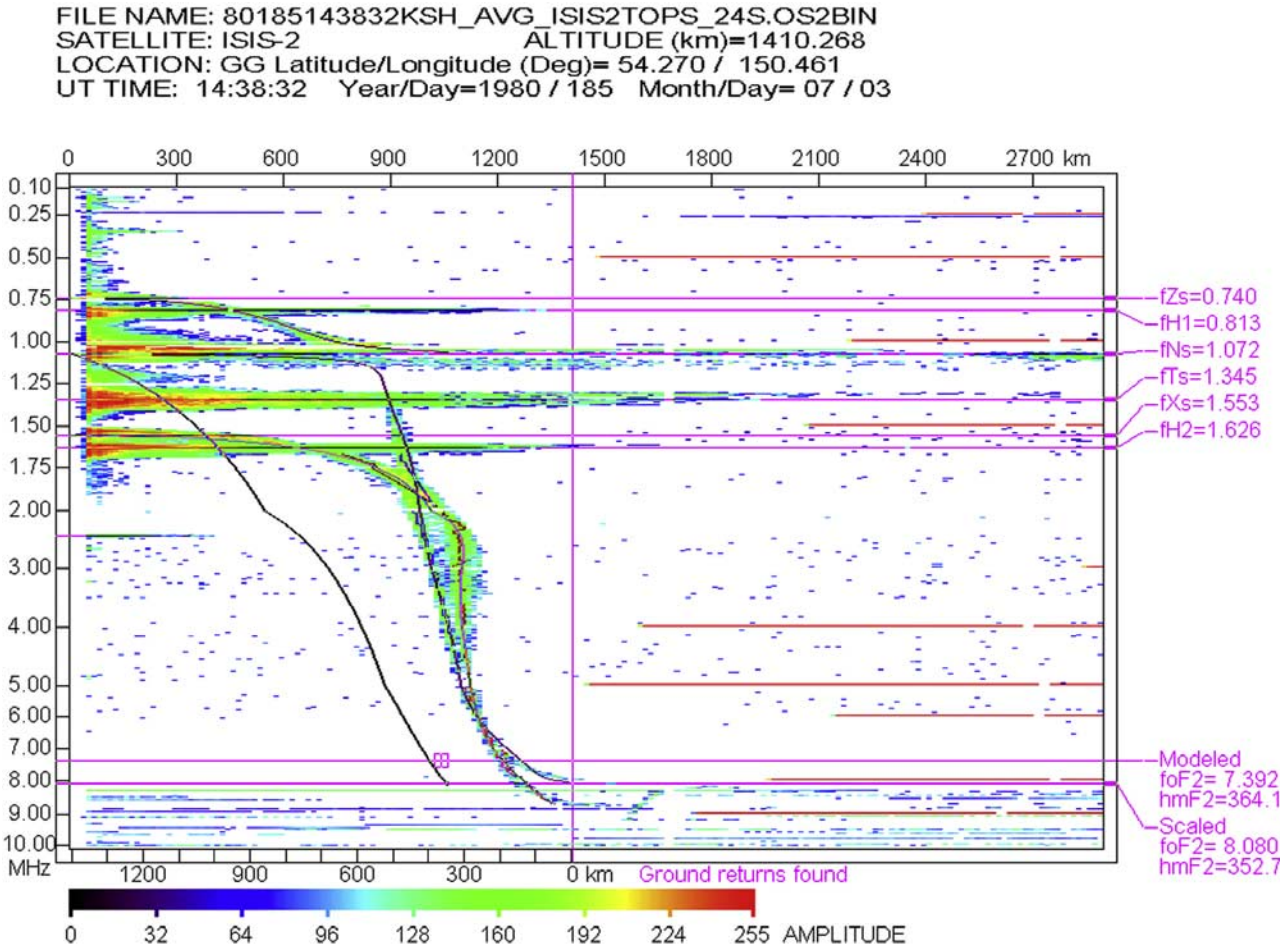

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