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MITHRAS: A brief description

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Between May 1981 and June 1982 an intensive campaign of 33 coordinated observations was carried out using the three incoherent-scatter radars capable of probing the auroral zone. During this period the groups operating the Dynamic Explorer satellites and the STARE radar made special efforts to acquire data coincident with the radar observations. The objective of these MITHRAS experiments and subsequent analysis is to further our understanding of the interactions of the magnetosphere, the ionosphere, and the thermosphere, with special emphasis on local time/universal time variations. Three experimental modes with different time resolution and spatial coverage were used to examine different aspects of these interactions. The analysis of the extensive data set involves collaboration among groups of experimenters as well as between experimenters and theoreticians.

INTRODUCTION

The purpose of the MITHRAS (Magnetosphere-Ionosphere-Thermosphere Radar Studies) project is to study in detail the high-latitude upper atmosphere using primarily three incoherent-scatter systems: Chatanika (Alaska); Millstone Hill (Massachusetts); and EISCAT (Scandinavia), the European Incoherent Scatter facility. The coordinated experiments were motivated by a need to better understand the coupling between the magnetosphere, the ionosphere, and the thermosphere. The upper atmosphere forms a dynamic system of considerable complexity which, so far, has hindered efforts to fully understand how this coupling takes place. A proper combination of detailed and complete observations, together with theoretical modeling, is necessary for progress to be made. Simultaneous experiments from different sites are necessary to resolve ambiguities between local time and universal time dependence of the observations.

The incoherent-scatter radar is a powerful research tool for the study of auroral zone phenomena such as ion convection, discrete and diffuse auroras, the mid-latitude trough, field-aligned currents, and neutral atmospheric circulation. The radars provide data over an extended altitude range and a wide geographical area. The radars enable us to observe the evolution of events with a time resolution of a few minutes to a few tens of minutes.

Measurements from the Scandinavian Twin Auroral Radar Experiment (STARE) were also utilized. STARE operates continuously and can measure electric fields over a large portion of Scandinavia [*Greenwald et al.*, 1978]. In addition, arrangements were made for the operation of the Dynamics Explorer (DE) satellites during the MITHRAS observations.

The Chatanika, Millstone Hill, and EISCAT systems have been described by *Leadabrand et al.* [1972], *Evans et al.* [1979], and *Folkestad et al.* [1983], respectively. The techniques to infer ionospheric parameters from the direct measurements are documented by *Wickwar* [1975], *de la Beaujardière et al.* [1980], and *Holt et al.* [1983*a*]. While Chatanika and Millstone are monostatic, EISCAT is tristatic. It comprises a transmitter-receiver station in Tromsø, Norway, and receiving stations in Kiruna, Sweden, and Sodankylä, Finland.

As illustrated in Figure 1, Chatanika and EISCAT are about 11 hours apart in magnetic local time (MLT), and Millstone Hill precedes Chatanika and follows EISCAT by more than 6 hours. Chatanika

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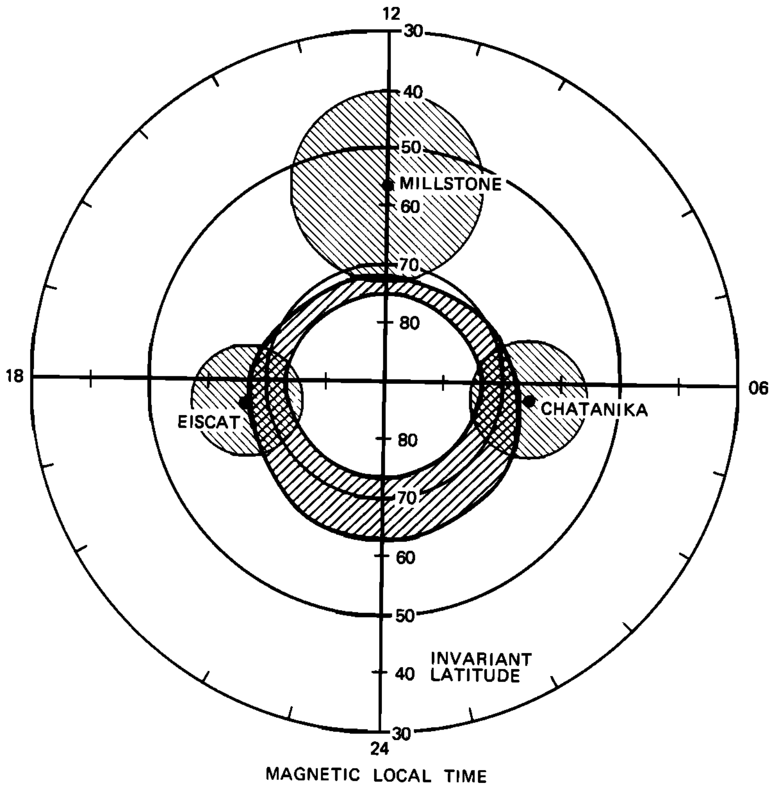

Fig. 1. MLT–invariant latitude plot of the positions of the EISCAT, Chatanika, and Millstone Hill radars when Millstone Hill is at magnetic noon. The auroral oval is that of *Feldstein and Starkov* [1968], for moderate activity ($Q = 5$). The small circles represent the F region area probed at 500-km altitude and with an elevation of 4°, 20°, and 20° for Millstone, Chatanika, and EISCAT, respectively. MLT was computed for the month of June.

and EISCAT are both located at about 65° invariant latitude, where they can probe the auroral zone in the E and F regions. Millstone Hill is located at 55° invariant latitude and can probe the auroral zone only in the F region. The coverage of the three radars at 500-km·altitude, and the auroral oval for moderate activity are also shown in Figure 1. The geographic and geomagnetic coordinates of the stations are listed in Table 1.

In this paper we describe the experimental modes and objectives, provide a catalog of the MITHRAS observations, and then briefly summarize some of the MITHRAS scientific results. MITHRAS is described in greater detail by *de la Beaujardière et al.* [1982].

EXPERIMENTAL MODES

Three distinct experiments were designed and carried out for the MITHRAS program; each had a different primary objective resulting in different spatial coverage and time resolution. Operating modes consistent with the experiment objectives were designed for Chatanika, Millstone Hill, and EISCAT. The objectives and operating modes are outlined in Table 2.

MITHRAS 1. This experiment was designed to provide F region measurements with the broadest

TABLE 1. Coordinates for Chatanika, EISCAT, and Millstone Hill Facilities

Parameter	Chatanika	EISCAT (Tromsø)	Millstone Hill
Geographic latitude	65.1°N	69.5°N	42.6°N
Geographic longitude	147.5°W	19.2°E	71.5°W
Invariant latitude, Λ*	65.1°	66.3°	55.2°
Dipole geomagnetic longitude	105°W	105°E	1.5°W
Λ coverage at 350-km altitude	56°–74°	61°–71°†	42°–70°
L value	5.6	6.2	3.1
Dip angle	77°	77.6°	70.5°
Declination	29°	−0.5°	−14.1°

*At 300-km altitude.

†These numbers reflect the largest coverage for the vector velocity measurements during the MITHRAS operations. The coverage for density and temperature is wider.

TABLE 2. The Three MITHRAS Experiments

Experiment	Objective	Time Resolution, min	Chatanika Mode	Millstone Hill Mode	EISCAT Mode
1	Widest latitudinal coverage	30 to 45	11 positions (5 pairs + 1 parallel to **B**)	350° azimuth scan at 4° elevation	CP(3).* Several positions along plane at 15° azimuth. Remote antennas intersect beam *F* region.
2	Shortest time resolution	10	Three positions (overhead measurements); short-pulse correlator for *E* region parameters	At two north azimuths, and for elevations 2° to 17°; *E* and *F* region measurements	CP(0) or CP(−1). Tromsø beam parallel to *B*. Remote antennas intersect at heights 110 to 700 km.
3	Intermediate time and latitude resolution	20	Elevation scan in meridian, followed by scan to the west	180° azimuth scan north of the station at 4° elevation	CP(3) (same as 1).

*CP is common program. The numbers in parentheses are as follows: 0 or −1 for single position mode; 3 for three or more positions along a magnetic meridian; 2 for three positions, one above each antenna.

possible latitudinal coverage. Large-scale studies of electric fields, temperatures, and ionization were emphasized. The time resolution of this experiment was 30 to 45 min.

The Chatanika radar was operated in an 11-position mode [*Foster et al.*, 1981]: five pairs of positions straddling the magnetic meridian plane, and one position parallel to the magnetic field, **B**. With this mode a large latitudinal coverage was possible in the *F* region, and at the same time the *E* region electrodynamic parameters could be determined close to the radar latitude. Every hour and a half, the radar was scanned in elevation in the magnetic meridian plane. This scan gave the cross section of the ionization profile as a function of height, with a fine latitudinal resolution.

The Millstone radar was operated at a fixed elevation (typically 4°) in an azimuth scan covering almost the full circle [*Holt et al.*, 1983*a*]. This operating mode had the advantage that longitudinal effects could be studied by comparing the measurements to the east and to the west. In 1982 the azimuth scans were followed by an elevation scan, horizon to horizon, in the geographic meridian.

During the initial operations, EISCAT could only be run with simple operating modes. The mode used during this phase is described under the MITHRAS 2 experiments. In December 1981, some latitudinal coverage was achieved with the system. Starting in January, later versions consisted of 11 or 16 positions in the 15° azimuth plane. The Sodankylä and Kiruna beams intersected the Tromsø beam at 325-km altitude.

MITHRAS 2. This experiment was directed primarily toward substorm studies of both the *E* and *F* regions with the best possible time resolution (10 min). To realize this time resolution, which is necessary to study substorm effects, this experiment concentrated on a narrow range of latitudes near the invariant latitude of Chatanika ($\Lambda = 65°$N). In addition to the *F* region electric field, temperatures, densities, and meridional wind, a wide range of *E* region parameters were obtained at Chatanika. These *E* region parameters included conductivities, electron energy deposition rates, differential energy spectra of precipitating electrons, neutral winds, currents, and Joule heating. At Tromsø, some of these *E* region parameters were also measured.

The operating mode for Chatanika consisted of a set of three positions, one parallel to the magnetic field and the two others on either side of the magnetic meridian at 70° elevation [*Rino et al.*, 1977]. The velocity and temperatures were obtained with a fine (9-km) altitude resolution for *E* region measurements, and with a coarser (50-km) resolution for the *F* region.

At Millstone Hill, initial observations were conducted at 4° elevation using a 64° azimuth scan centered north on the magnetic meridian. At *F* region altitudes (200 to 500 km) the resulting invariant latitude coverage was 61° to 69°. Later, a second type of MITHRAS 2 program consisted of elevation scans from 2° to 17°, at azimuths 15° on either side of the magnetic meridian, covering the invariant latitudes from 60° to 72° for *F* region altitudes. This program used a shorter pulse length at the lowest elevation angles in order to obtain *E* region parameters.

The EISCAT transmitting antenna was held fixed, parallel to the magnetic field. For some experiments, the two receiving stations scanned the Tromsø beam at six discrete heights between 110- and 700-km altitude. In other experiments the remote stations were held fixed, intersecting the Tromsø beam at about 300-km altitude.

MITHRAS 3. This experiment was directed at examining *E* and *F* region morphology with a time resolution between those afforded by programs 1 and 2 (i.e., about 20 min). For Chatanika and EISCAT it provided latitudinal coverage for both *E* and *F* regions. It was useful in identifying and following the evolution of ionization features (e.g., diffuse aurora, trough, and *F* region enhancements) as well as the variations of electric field, temperatures, currents, precipitating electron energy spectra, and the energy deposition rate associated with these features.

The Chatanika radar operated in a set of two scans [*de la Beaujardière et al.*, 1981]. It completed one elevation scan in the magnetic meridian and then one scan to the west along a path such that at each invariant latitude the radar sampled the ionosphere at the same magnetic local time that was sampled during the elevation scan. The mode for EISCAT was the same as that for MITHRAS 1. Millstone scanned in azimuth over the 180° north of the radar, at an elevation of 4°.

CATALOG OF MITHRAS OBSERVATIONS

A summary of MITHRAS operations at the three radars is given in Table 3. The operating modes are identified by the descriptions listed in the previous section. The times listed are the start and end times at each radar. Twenty-nine MITHRAS experiments were made before Chatanika was disassembled in preparation for its move to Greenland. There are a total of 33 MITHRAS experiments, covering a period of just over 1 year. The first observations started before EISCAT was operational. By special agreement the MITHRAS observations were continued between Millstone and EISCAT after the Chatanika disassembly. The two-way and three-way overlap hours indicate the duration of the periods when data were collected at two of the three and at all three radars. The sum of the 3-hourly *Kp* values for each 24-hour period is listed to indicate the global magnetic conditions for the cooperative experiments. Fortunately, each experiment type occurred during both quiet and active geomagnetic conditions.

PRELIMINARY SCIENTIFIC RESULTS

The data analysis phase of the MITHRAS program has started. Among the preliminary results obtained we can cite the following:

Ionosphere. For a given electric field the *F* region ion temperature tends to be higher in the postmidnight sector than in the premidnight sector. This asymmetry was explained by the fact that ion-neutral frictional heating is more pronounced and longer lasting in the morning than in the evening sector. In the evening, ion drag is more effective at coupling the neutrals to the ions; the time constant for the coupling is less than 1 hour. In the morning this time constant becomes very long, more than 7 hours, because of the low electron density. Thus the ion and neutral motions are essentially decoupled [*Baron and Wand*, 1983]. In a separate study, currently in progress, ionospheric densities and temperatures were compared for the three radars for selected periods, and between the radars and the model ionosphere of *Elkins* [1973]. In a third study, the nighttime *F* region density was compared for the three radars. It was found that the densities were largest over EISCAT and were lowest over Millstone Hill. This inequality was attributed to the offset of the geographic and geomagnetic poles. When each radar is in the midnight sector, the corresponding cusp region is at a lower latitude for EISCAT than for Millstone. In other words, the relative positions of the terminator and the cusp determine how much ionization is contained in the flux tubes that convect across the polar cap [*de la Beaujardière et al.*, 1983*b*].

Thermosphere. A method was developed to determine auroral zone values for the exospheric temperature and atomic oxygen concentration, even in the presence of Joule heating. These thermospheric parameters were obtained for several periods, and the EISCAT and Chatanika values compared [*Alcaydé et al.*, 1982, 1983]. A study is now in progress to determine the seasonal and solar cycle dependence of the exospheric temperature, using EISCAT and Chatanika data.

The EISCAT and Chatanika meridional winds between 200 and 300 km have been compared to determine the major features and driving forces [*Wickwar et al.*, 1983]. During the night there is a strong equatorward wind. The EISCAT/Chatanika comparison indicates that the wind is controlled to a large extent by magnetospheric effects, possibly arising from ion drag. During nights when the electric field was large,

TABLE 3. MITHRAS Operations (May 1981 Through June 1982)

Day	Date*	Time* (Start–End)			Two-Way Overlap,† hours	Three-Way Overlap,† hours	ΣKp	Mode
		Chatanika	Millstone Hill	EISCAT				
133	May 13	0018–2400	2135–		2.4	···	16–	MITHRAS 2
134	May 14		–0400		···	···	25	
143	May 23	1555–	1425–		8.1	···	25+	MITHRAS 1
144	May 24	–1837	–1950		13.0	···	26+	
161	June 10	0044–	0005–		22.7	···	9	MITHRAS 3
162	June 11	–0130	–0400		1.5	···	13	
174	June 23	2050–2340	2210–		1.5	···	10–	MITHRAS 2
175	June 24		–		···	···	19+	
176	June 25		–0400		···	···	22	
178	June 27	0358–	0335–		19.7	···	20–	MITHRAS 1
179	June 28	–0505	–1725		5.1	···	18	
185	July 4	0158–	0210–		20.4	···	16–	MITHRAS 1
186	July 5	–0358	–		4.0	···	22–	
187	July 6		–1215		···	···	27–	
195	July 14	2200–			···	···	14–	MITHRAS 2
196	July 15	–	1510–		8.8	···	7–	
197	July 16	–0012	–1520		0.2	···	16+	
202	July 21	2152–			···	···	13–	MITHRAS 3
203	July 22	–2359	0112–		17.1	···	28+	
204	July 23		–0030		···	···	34 –	
213	Aug. 1		0550–		···	···	26–	MITHRAS 1
214	Aug. 2	0208–	–2330		20.8	···	22–	
215	Aug. 3	–0358			···	···	26–	
218	Aug. 6		0720–		···	···	21+	MITHRAS 3
219	Aug. 7		–0030		···	···	17+	
223	Aug. 11		2005–		···	···	22+	MITHRAS 1
224	Aug. 12		–		···	···	18–	
225	Aug. 13		–1125		···	···	18+	
258	Sept. 15		1850–		···	···	17+	MITHRAS 1
259	Sept. 16		–2330	0900–	14.5	···	15–	CP(–1)
260	Sept. 17			–0800	···	···	9	
265	Sept. 22		1318–		···	···	20	MITHRAS 3
266	Sept. 23		–		···	···	8+	
267	Sept. 24		–1600		···	···	16	
272	Sept. 29		1949–		···	···	20+	MITHRAS 2
273	Sept. 30	0130–	–	1130–	18.9	12.5	24–	CP(–1)
274	Oct. 1	–0138	–0346	–0900	3.8	1.6	18	
279	Oct. 6			2200–	···	···	12–	MITHRAS 3
280	Oct. 7	0011–	2236–	–2120	13.4	···	32	CP(–1)
281	Oct. 8	–1214	–2400		12.2	···	30	
297	Oct. 24		0217–		···	···	22–	MITHRAS 1
298	Oct. 25	0031–	–	1630–	23.0	5.1	24+	CP(0)
299	Oct. 26	–	–1328	–0900	13.0	8.5	18–	
300	Oct. 27	–0009			···	···	18	
300	Oct. 27		2129–		···	···	18	MITHRAS 2
301	Oct. 28	0004–	–		22.9	···	26	
302	Oct. 29	–0200	–0415		2.0		20	

TABLE 3. (continued)

Day	Date*	Time* (Start–End)			Two-Way Overlap,† hours	Three-Way Overlap,† hours	ΣKp	Mode
		Chatanika	Millstone Hill	EISCAT				
314	Nov. 10		2130–		···	···	21−	MITHRAS 3
315	Nov. 11	0000–	–	0900–1453	21.9	5.9	32−	CP(0)
316	Nov. 12	–0213	–0135		1.6	···	30−	
321	Nov. 17		2124–		···	···	33+	MITHRAS 2
322	Nov. 18	0017–	–	0900–	22.6	15.0	31	CP(0)
323	Nov. 19	–0001	–0500	–0900	5.0	···	23+	
325	Nov. 21	0017–	0312–		20.5	···	23+	MITHRAS 1
326	Nov. 22	–0201	–		1.9	···	19+	
327	Nov. 23		–0926		···	···	27	
339	Dec. 5	1702–	0313–		4.2	···	17+	MITHRAS 1
340	Dec. 6	–1707	–0330		3.5	···	8+	
342	Dec. 8	2143–	2235–	1500–	2.3	1.4	22+	MITHRAS 3
343	Dec. 9	–2400	–0456	–2020	17.3	4.4	20−	CP(−3*e*)
349	Dec. 15	2241–	2146–	1500–	2.2	1.3	10+	MITHRAS 2
350	Dec. 16	–	–	–1940	21.5	17.2	9−	CP(−3s)
351	Dec. 17	–0010	–0449		0.2	···	11	
9	Jan. 9		0305–		···	···	8	MITHRAS 1
10	Jan. 10	0620–	–		17.7	···	7−	
11	Jan. 11	–0803	–1418		8.0	···	10+	
19	Jan. 19	1800–	2116–		2.7	···	6+	MITHRAS 2
20	Jan. 20	–2005	–	1500–2300	19.7	1.2	12+	CP(−3e)
21	Jan. 21		–0458				22	
26	Jan. 26	1818–	2121–	1500–	5.7	2.7	13	MITHRAS 3
27	Jan. 27	–	–	–2258	24.0	21.0	21+	CP(3)
28	Jan. 28	–0010	–0129		0.2	···	24	
30	Jan. 30		0306–		···	···	29	MITHRAS 1
31	Jan. 31	0608–	–	1000–2345	15.6	12.4	34−	CP(3)
32	Feb. 1	–1320	–1332		13.3	···	34	
40	Feb. 9	1550–	1042–		8.2	···	24	MITHRAS 3
41	Feb. 10	–2307	–1512		15.2	···	33+	
47	Feb. 16	1805–	2031–		3.5	···	13+	MITHRAS 2
48	Feb. 17	–	–		23.4	···	30+	
49	Feb. 18	–0003	–0459		···	···	34+	
114	April 24		0441–			···	21	MITHRAS 1
115	April 25		–	1210–	10.0	···	37+	CP(3)
116	April 26		–1227	–1000	10.0	···	15−	
128	May 8		0153–			···	10	MITHRAS 1
129	May 9		–2000	1018–	8.8	···	15	CP(0)
130	May 10			–1003		···	11−	
138	May 18		2008–	1500–	3.9	···	26+	MITHRAS 3
139	May 19		–2400	–2300	23.0	···	21	CP(−2)
140	May 20		–0358			···	17	
166	June 15		2012–				30	MITHRAS 1
167	June 16		–	1100–	13.0	···	19+	CP(3)
168	June 17		–0358	–1100	4.0	···	13−	

*Dates and times are UT.

†Data gaps of > 20 min duration excluded from overlap time calculation.

there was a second equatorward wind increase that may have been related to Joule heating.

A study is now in progress concerning the electrodynamic parameters of the ionosphere/magnetosphere system. This work involves a comparison of the MITHRAS electric fields measured at several longitudes with those deduced from the various International Magnetospheric Study chains of magnetometers. The technique to compute the global electric fields and field-aligned currents from the magnetometer data has been described by *Kamide et al.* [1982]. It is quite complex and relies heavily on a model of conductivity. The use of conductivities from Chatanika and EISCAT, along with those deduced from satellites, should be a significant improvement over the available models. The calculations will then be further constrained by having to obtain convection electric fields that match those from the three radars.

Magnetosphere. Detailed case studies dealt with the effect of substorms on convection. A three-radar comparison of the substorm electric field signature [*de la Beaujardière et al.*, 1983*a*] revealed that the signature depends primarily on the local time when the observation is made. The cross–polar cap potential was also estimated from radar electric fields in the dawn or dusk sectors. In another study, it was shown that intense electric fields associated with substorms can be a dominant factor in the formation of ionospheric troughs [*Holt et al.*, 1983*b*; *Evans et al.*, 1983]. Subauroral electric fields were observed during a period of prolonged magnetic activity on November 11, 1981 [*Senior*, 1982]. For one MITHRAS period when the interplanetary magnetic field (IMF) components were south and away, *Heelis et al.* [1983] determined the large-scale ion convection using data from three radars in conjunction with several DE 2 passes. The dusk cell had a circular shape such that its poleward perimeter extended into the dawn sector. The dawn cell was smaller and crescent shaped. Another study also dealt with an extended period when the IMF was south and away (November 18, 1981). The electric fields seen by Chatanika, Millstone, and EISCAT were very intense in the dawn and dusk sectors, and the electric field reversal in the midnight sector occurred at a very early local time at the three radars. G. Caudal et al. (unpublished manuscript, 1983) suggest that for at least 10 hours the global plasma convection pattern remained fairly uniform and was expanded and rotated toward early hours.

Empirical models. Models are being constructed to characterize the day and night conductivities, the electric fields, the E and F region densities, and the exospheric temperature. These models yield average values of the latitudinal variations of the radar parameters. They depend on quantities such as Kp, solar flux, IMF, solar zenith angle, and precipitation. Particular attention has been given to the average convection pattern [*Foster*, 1983; *Oliver et al.*, 1983; J. M. Holt et al., unpublished manuscript, 1983]. In the work by *Foster* [1984] the average convection is mapped into the outer magnetosphere. These models are important in their own right, but they also provide a baseline to which particular data sets can be compared.

Theoretical model. A theoretical model of the temporal variation and global effects of ring current shielding has been developed [*Senior and Blanc*, 1984]. This model can be used to interpret the subauroral electric fields observed on November 11, 1981.

A study is under way to model the convection and electron density measurements from Chatanika and Millstone Hill on June 27, 1981. This effort uses the convection and ionospheric models described by *Schunk and Raitt* [1980] and *Sojka et al.* [1981]. It is part of a systematic extension of these comparisons from one radar [*Sojka et al.*, 1983] to two, and then three, radars.

DATA AVAILABILITY

The MITHRAS data set of coincident auroral zone observations is available to interested scientists. The exchange of data among groups is facilitated by the adoption of a simple, but general, tape-formatting procedure. It is the procedure proposed for the incoherent-scatter data base at the National Center for Atmospheric Research. Data exchange is further eased by having all the incoherent-scatter data centrally available at SRI International. Scientists interested in using this data set should contact either of the first two authors of this paper.

CONCLUSIONS

An intensive campaign of coordinated auroral zone observations using three incoherent-scatter radars (Chatanika, Millstone Hill, and EISCAT) took place between May 1981 and June 1982. Coincident measurements were also made with STARE and the DE satellite. The purpose of these observations is to acquire a better understanding of the magnetosphere-ionosphere-thermosphere interactions by monitoring the auroral zone from stations widely separated in longitude.

Three types of MITHRAS experiments were conducted, each with a different temporal and spatial resolution. The exact times of observations and an indication of the magnetic activity are given in the catalog of MITHRAS experiments. This unique data set is open to the scientific community, and analyses by several groups are under way.

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