

AD 729203

AFOSK

Final Report

# HIGH-LATITUDE AURORAL-RADAR AND HF-DOPPLER STUDIES OF GEOACOUSTIC PHENOMENA

By: E. J. FREMOUW N. J. F. CHANG

Prepared for:

DIRECTOR  
ADVANCED RESEARCH PROJECTS AGENCY  
ARLINGTON, VIRGINIA 22209

CONTRACT F44620-70-C-0117

DISTRIBUTION STATEMENT A  
Approved for public release;  
Distribution Unlimited



**STANFORD RESEARCH INSTITUTE**  
Menlo Park, California 94025 • U.S.A.

Reproduced by  
**NATIONAL TECHNICAL  
INFORMATION SERVICE**  
Springfield, Va. 22151

# DISCLAIMER NOTICE

THIS DOCUMENT IS THE BEST  
QUALITY AVAILABLE.

COPY FURNISHED CONTAINED  
A SIGNIFICANT NUMBER OF  
PAGES WHICH DO NOT  
REPRODUCE LEGIBLY.

## DOCUMENT CONTROL DATA - R &amp; D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Stanford Research Institute Menlo Park, California		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP N/A	
3. REPORT TITLE HIGH-LATITUDE AURORAL-RADAR AND HF-DOPPLER STUDIES OF GEOACOUSTIC PHENOMENA			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Scientific Final			
5. AUTHOR(S) (First name, middle initial, last name) Edward J. Fremouw Norman J. F. Chang			
6. REPORT DATE July 1971	7a. TOTAL NO. OF PAGES 129	7b. NO. OF REFS 59	
8a. CONTRACT OR GRANT NO F44620-70-C-0117		8b. ORIGINATOR'S REPORT NUMBER(S) Final Report SRI Project 8706	
b. PROJECT NO AO 1722	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)		
c. 62701D			
d.			
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES TECH OTHER		12. SPONSORING MILITARY ACTIVITY Air Force Office of Scientific Research 1400 Wilson Boulevard (NPG) Arlington, Virginia 22209	
13. ABSTRACT A coordinated program of high-latitude ionospheric observations related to geoacoustic research has been carried out at Homer, Alaska. The program consisted of two types of observations: an auroral-radar search for sources of ground-detected Auroral Infrasound Waves (AIW's) and HF-Doppler soundings of the F layer for observation of Traveling Ionospheric Disturbances (TID's). A 139-MHz radar employing 75-microsecond pulses and a 60-foot antenna with its beam fixed on the E layer just north of College, Alaska, was used in the search for AIW sources. Results were compared with records of AIW's collected at College by the University of Alaska and were consistent with earlier statistical results indicating that radar aurora and AIW's are related generally. A clearcut and consistent radar signature of AIW sources was not found, due, it is believed, to limitations of the present radar instrumentation. It was established, however, that AIW's often (although not always) follow rapid southward motion of radar-auroral features but apparently do not follow similar--or even faster--northward motions. This observation is consistent with a recent suggestion that AIW's result from Pedersen drift of ions associated with auroral arcs moving supersonically southward. A byproduct of the radar search has been identification of a distinctive radar signature of the poleward-expansion phase of auroral (or "polar magnetic") substorms. The radar observations were conducted during October and November of 1970, as were the related HF-Doppler measurements. The pilot HF sounding program demonstrated the feasibility of observing TID's at a location close to one of			



STANFORD RESEARCH INSTITUTE  
Menlo Park, California 94025 · U S A

*Final Report*

July 1971

## HIGH-LATITUDE AURORAL-RADAR AND HF-DOPPLER STUDIES OF GEOACOUSTIC PHENOMENA

*By:* E. J. FREMOUW N. J. F. CHANG

*Prepared for:*

DIRECTOR  
ADVANCED RESEARCH PROJECTS AGENCY  
ARLINGTON, VIRGINIA 22209

*Contract No:* (AFOSR) F44620-70-C-0117  
*Contract Period:* 1 JUNE 1970 THROUGH  
31 JULY 1971

*Contract Amount:* \$82,733

*Program Code No:* OF10

*Principal Investigator:* E. J. FREMOUW  
(415) 326-6200  
Ext. 2596

*Project Scientist:* W. J. BEST  
(202) 694-6456

SRI Project 8706

*Approved by:*

DAVID A. JOHNSON, *Director*  
*Radio Physics Laboratory*

RAY L. LEADABRAND, *Executive Director*  
*Electronics and Radio Sciences Division*

Copy No. .... 15

④ their suspected source regions, the auroral zone, and revealed long trains of TID's--lasting for hours--that are not seen in similar mid-latitude observations. The limited results obtained are suggestive of two source regions--one auroral and one non-auroral--for high-latitude TID's. In addition, other types of F-layer density perturbations were observed, including discovery of what are believed to be two previously undetected types.

**BLANK PAGE**

## ABSTRACT

A coordinated program of high-latitude ionospheric observations related to geoaoustic research has been carried out at Homer, Alaska. The program consisted of two types of observations: an auroral-radar search for sources of ground-detected Auroral Infrasonic Waves (AIW's) and HF-Doppler soundings of the F layer for observation of Traveling Ionospheric Disturbances (TID's). A 139-MHz radar employing 75-microsecond pulses and a 60-foot antenna with its beam fixed on the E layer just north of College, Alaska, was used in the search for AIW sources. Results were compared with records of AIW's collected at College by the University of Alaska and were consistent with earlier statistical results indicating that radar aurora and AIW's are related generally. A clearcut and consistent radar signature of AIW sources was not found, due, it is believed, to limitations of the present radar instrumentation. It was established, however, that AIW's often (although not always) follow rapid southward motion of radar-aurora features but apparently do not follow similar--or even faster--northward motions. This observation is consistent with a recent suggestion that AIW's result from Pedersen drift of ions associated with auroral arcs moving supersonically southward. A byproduct of the radar search has been identification of a distinctive radar signature of the poleward-expansion phase of auroral (or "polar magnetic") substorms. The radar observations were conducted during October and November of 1970, as were the related HF-Doppler measurements. The pilot HF sounding program demonstrated the feasibility of observing TID's at a location close to one of their suspected source regions, the auroral zone, and revealed long trains of TID's--lasting for hours--that are not seen in similar mid-latitude observations. The limited results obtained are suggestive of two

source regions--one auroral and one non-auroral--for high-latitude TID's. In addition, other types of F-layer density perturbations were observed, including discovery of what are believed to be two previously undetected types.



CONTENTS

ABSTRACT. . . . .	iii
LIST OF ILLUSTRATIONS . . . . .	vii
LIST OF TABLES. . . . .	xi
ACKNOWLEDGMENTS . . . . .	xiii
I SUMMARY . . . . .	1
II BACKGROUND AND OBJECTIVES . . . . .	7
III RADAR SEARCH FOR SOURCES OF AURORAL INFRASONIC WAVES. . . . .	15
A. Radar Operation. . . . .	15
B. Data Handling. . . . .	22
C. Results Concerning AIW Sources . . . . .	25
D. Auroral-Substorm Radar Signature--An Unexpected Byproduct. . . . .	39
IV HF-DOPPLER STUDIES OF F-LAYER PHENOMENA . . . . .	47
A. The CW-Doppler Technique . . . . .	47
1. Doppler Signature Produced by Ionospheric Disturbances. . . . .	47
2. The Alaskan HF Sounder Array. . . . .	58
B. Data Overview. . . . .	65
C. The High-Latitude Observations--Discussion of Results. . . . .	70
1. Traveling Ionospheric Disturbances. . . . .	72
a. Medium-Scale TID's . . . . .	73
b. Very Large TID's . . . . .	86

CONTENTS (Continued)

2.	Doppler Fluctuations Associated with Geomagnetic Variations. . . . .	89
3.	Newly Discovered Types of Events. . . . .	91
D.	Relationship Between TID's and AIW's . . . . .	97
V	CONCLUSIONS . . . . .	101
	REFERENCES. . . . .	107

DD FORM 1473

ILLUSTRATIONS

Figure 1	The Auroral Radar Antenna and Vans at the Ohlson Mt. Field Site Near Homer, Alaska. . . . .	16
Figure 2	Plan View of Observing Geometry over Alaska from the Homer Radar. . . . .	19
Figure 3	Radar Observing Geometry in the Elevation Plane. . . . .	21
Figure 4	Seven Examples of Quick-Look, Range-Time-Intensity (RTI) Records. . . . .	23
Figure 5	Two Examples of RTI Records Used in Detailed Analysis . . . . .	26
Figure 6	Map Depicting Example of Coincidence Between Radar Coverage and Path of an AIW Arriving At College, Alaska . . . . .	30
Figure 7	Two Distinctive Radar-Auroral Developments and an AIW Following One of Them. . . . .	32
Figure 8	Comparison of Visual-Auroral Development, Radar-Auroral Development, and AIW Record. . . . .	34
Figure 9	Another Comparison of Visual-Auroral, Radar-Auroral, and AIW Developments . . . . .	37
Figure 10	Comparison of College Magnetogram with Homer Radar RTI Record Showing Three Distinctive Developments. . . . .	41
Figure 11	Two More Examples of Distinctive Radar-Auroral Forms Moving Rapidly Northward . . . . .	42
Figure 12	The All-Sky-Camera, Magnetogram, and Newly Discovered Auroral-Radar Signatures of a Substorm Poleward Expansion that Reached College, Alaska, at 1042 on 7 November 1970. . . . .	44
Figure 13	Doppler Shift and Path Length for a Sample Disturbance. . . . .	51
Figure 14	Traveling Ionospheric Disturbance with Five Cycles of Regular Fluctuations Observed over Boulder, Colorado . . . . .	53

ILLUSTRATIONS (Continued)

Figure 15	Traveling Ionospheric Disturbance Observed over Boulder, Colorado . . . . .	54
Figure 16	Simultaneous Frequency and Signal-Strength Recordings of a Steep-Incidence, 5.054 MHz Radio Signal Illustrating Amplitude Focusing when $d\Delta f/dt$ is Large. . . . .	55
Figure 17	Illustration of the Specular Reflector and the Nature of Doppler Shifts of Radio Signals Reflected From It . . . . .	57
Figure 18	Alaskan CW-Doppler Array. . . . .	59
Figure 19	Block Diagram of Alaska CW-Doppler Network. . . . .	60
Figure 20	Doppler Spectrum of Signals from Wildwood and Seward over a 24-hour Period. . . . .	63
Figure 21	Summary of CW-Doppler Data and Other Pertinent Information . . . . .	66
Figure 22(a)	Doppler Spectrum of Signals from Seward and Wildwood Showing Diurnal Variation. . . . .	68
Figure 22(b)	Horizontal Component of Geomagnetic Field for 5 November 1970 . . . . .	68
Figure 23	Diurnal Doppler Record at Mid-Latitude, 3.3 MHz . . . . .	70
Figure 24	Doppler Spectrum for a 1180 km Path near the Magnetic Equator. . . . .	71
Figure 25(a)	Long Duration Medium-Scale TID Observed over the Homer CW Doppler Network. . . . .	75
Figure 25(b)	Horizontal Component of the Geomagnetic Field for 13-14 November 1970 . . . . .	77
Figure 26	Tracing of a Portion of the 13-14 November TID Showing the Time Shifts of the Disturbance on the Seward and Wildwood Paths Relative to the Elmendorf Path. . . . .	78
Figure 27	Polar View Showing the Direction of Arrival of the 13-14 November TID Relative to the Position of the Auroral Oval at 1800 and 2200 UT . . . . .	79

ILLUSTRATIONS (Continued)

Figure 28	A Long-Duration Medium-Scale TID Observed over the Seward and Wildwood Paths. . . . .	81
Figure 29	Doppler Spectra Showing (a) Switchback Signatures, and (b) Modulation Effect in the Doppler Traces Between 1600 and 1700 UT . . . . .	82
Figure 30	Doppler Spectra Showing Switchback Signatures Between 0600 and 0700 UT . . . . .	83
Figure 31	Highly Dispersive TID Detected on the Seward and Wildwood Paths . . . . .	84
Figure 32	Doppler Fluctuations Associated with Geomagnetic Variations . . . . .	87
Figure 33	Polar Projection of the Position of the Auroral Oval at 0400 UT and the Calculated Direction of Arrival of the 17 October 1970 TID . . . . .	88
Figure 34	Doppler Fluctuations that Resemble Post-Sunset Equatorial Signatures. . . . .	92
Figure 35	Doppler Records Showing Modulation in the Spectra. . .	94
Figure 36	Portion of 9 November 1970 Doppler Records Showing an Unusual Disturbance near 1000 UT. . . . .	96

TABLES

Table 1	Summary of TID Source Suggestions . . . . .	11
Table 2	Pertinent Radar Characteristics . . . . .	17
Table 3	Available AIW and Auroral Data. . . . .	27
Table 4	Summary of Some Useful Formulae . . . . .	48
Table 5	Summary of Format Used for the Transmitter Keyers . . . .	61
Table 6	TID's Observed with the Alaskan CW-Doppler Network. . . .	74

## ACKNOWLEDGMENT

The active cooperation of Dr. Charles Wilson of the University of Alaska's Geophysical Institute is hereby acknowledged with appreciation. Dr. Wilson provided the Auroral Infrasonic Wave (AIW), data, the auroral all-sky-camera data, and the magnetic activity data from College, Alaska, that were used in this study. In addition, discussions with Dr. Wilson on interpretation of the AIW, visual auroral, and geomagnetic data were most useful.

Many of our colleagues at Stanford Research Institute contributed importantly to the success of the auroral radar and the HF-Doppler program. In particular the assistance of James Hodges, Franklin Firth, and Raymond Irvine in the radar and Doppler data collection is greatly appreciated. Discussions with Boyd Fair on the Doppler equipment were valuable.

The slow-speed tape recorder was loaned to SRI by NOAA. The authors thank John E. Jones of NOAA for making the loan possible. Permission to locate the Doppler transmitters on Air Force property is gratefully acknowledged. Particular thanks are due to Lt. Matthews who was stationed at Wildwood Air Force Station, and to Sgt. Caro who was stationed at Elmendorf Air Force Base for their hospitality.

Permission from DASA to use the Homer auroral radar facility, without which this research would have been impossible, is gratefully acknowledged.

**BLANK PAGE**



## I SUMMARY

This document reports the results of a coordinated program of ionospheric observations pertaining to high-latitude geoacoustics research. The program consisted of two types of measurements, aimed respectively at study of Auroral Infrasonic Waves (AIW's) and Traveling Ionospheric Disturbances (TID's). Understanding these two phenomena is relevant to the problem of detecting and interpreting remote, man-made atmospheric pressure disturbances such as those that result from nuclear detonations.

The phenomena represent sources of naturally occurring geoacoustic energy, which comprises the noise background in which monitoring systems must operate. Coordinated study of the two phenomena bears particularly on the relationship between the noise background of complementary systems that measure, respectively, perturbations in surface-level pressure and disturbances in the density of the ionospheric F layer at heights of several hundred kilometers.

The two types of observations conducted both involved remote sensing of the ionosphere. The AIW-related research consisted of performing and interpreting observations of radar backscattering regions in the aurorally disturbed E layer, commonly called "radar aurora." Earlier work (Fremouw, 1970) had shown that AIW's detected with surface-level microbarographs were closely related to radar aurora in a statistical sense. Radar aurora had been found to be present over Alaska in periods preceding all of 62 AIW's received independently by Wilson (private communication) at College, Alaska, and in nearly all cases to be present in the direction from which the AIW's arrived. Rapidly moving radar-auroral patches or forms were found to be especially closely related to AIW's.

Wilson (1969a) has found that AIW's follow rapid motions of prominent features in visual auroral forms--often entire arcs--and has interpreted them as shock waves created when the auroral forms are moving supersonically. Against the background of a statistical relationship of AIW's with radar aurora and a specific relationship with fast-moving visual aurora, a search was instituted for a specific radar-auroral signature of AIW's.

The search and its results are reported herein; it was conducted by Stanford Research Institute (SRI) at its auroral radar site near Homer, Alaska. The Homer radar is a multi-frequency instrument, but the current work was conducted primarily at 139 MHz. The 139-MHz radar was operated with a 75-microsecond pulse, providing a range resolution of 12 km, and a 60-foot antenna, providing angular resolution of 9 degrees. The antenna is fully steerable but was operated in fixed position, for the most part, in this program.

The antenna beam was centered, at the 110-km altitude from which most auroral echoes are received, on a region just north of College, Alaska, where AIW observations were being conducted by Wilson at the University of Alaska. This resulted in radar illumination of the region most likely to contain sources of AIW's detected at College and the region monitored for visual auroral forms by means of all-sky cameras operated by the Geophysical Institute of the University of Alaska.

The antenna was held fixed most of the time in order to facilitate measuring the rate of change in range from Homer to the radar auroral forms, since rapid north-south motion was anticipated as a hallmark of forms associated with AIW. The antenna was briefly scanned in elevation once every few minutes to increase coverage and moved slightly in azimuth every hour to maximize chances of detecting AIW sources, making use of the known diurnal variation of AIW azimuth of arrival at College (Wilson, 1969a). Observations were conducted for from six to eight hours (in a few instances,

longer) each night during six weeks in October and November of 1970, with the exception of one night during which high winds required stowing the antenna. The radar and the observations are described more fully in Section III-A.

In general, the current observations corroborated the earlier finding that AIW's tend to originate at times of and in regions of bright, extensive radar auroral activity, but the distinctive feature of radar auroral records hoped for as a clear-cut radar signature of AIW sources was not found. It is believed that the lack of a consistent signature results from instrumental limitations in the present radar, which nonetheless was able to disclose information relevant to understanding the source mechanism of AIW's.

It was observed that AIW's often (although not always) followed the rapid motion of identifiable radar-auroral forms southward to near the College zenith. On the other hand, several striking cases of distinct radar-auroral forms moving rapidly from the south to the north past the College zenith were observed, and not a single one of them was followed by an AIW at College. This difference between southward- and northward-moving forms is consistent with a recent suggestion by Wilson (private communication) that AIW's result from momentum imparted to the neutral atmosphere, at the height of the E layer, by collisions with ions undergoing a Pedersen drift due to the presence of electric fields near auroral arcs.

The observation of the radar-auroral forms in rapid northward motion, as a distinctly identifiable phase of auroral-radar development, constitutes an unexpected byproduct of the present research. It resulted from the shorter pulses and slightly modified data-reduction techniques used for the AIW program as contrasted with other auroral-radar observing programs. Comparison of the data with all-sky-camera photographs of the aurora made

at College and with College magnetograms disclosed that what has been discovered is the radar signature of the poleward-expansion phase of auroral (or "polar magnetic") substorms. This result is described in Section III-D, following a more general discussion of results of the radar observations in Section III-C.

Given the lack of a uniquely identified radar signature for AIW sources found in the present work, a further search with the present instrumentation does not seem warranted. A fundamental modification of the Homer radar, described briefly in Section V, is planned for late 1972. Since this modification will greatly facilitate the radar's ability to map and track fast-moving radar auroral forms of the type believed to contain AIW sources, a one-year moratorium on the radar search is recommended, pending readiness of the new instrument. In the meantime, study of the newly discovered auroral-substorm signatures with the existing radar holds much more scientific promise.

Unlike the radar-auroral/AIW research, which followed earlier, similar observations, the research on high-latitude TID constituted a pilot program. Its first goal was to test the feasibility of performing TID observations by the HF-Doppler sounding technique at a location close to one of the suspected source regions of these propagating F-layer disturbances, the auroral zone. This goal was successfully achieved, with such observations in fact being performed at Homer, Alaska, in the same autumnal period as the radar observations (i.e., October and November of 1970). The technique and apparatus used are described in Section IV-A.

The observations consisted of transmitting continuous-wave (CW) signals from three locations around the Kenai Peninsula in Alaska, with all signals being received at the Homer radar site. Propagation conditions and some transmitter difficulties limited the amount of data obtained,

but sufficient data were collected to permit observation of several interesting types of F-layer disturbances, including the TID's that were sought.

In the case of some TID's, it was possible to measure the arrival direction and speed of propagation; these limited results are consistent with the possibility of two distinct source mechanisms. Two mechanisms--one of meteorological and one of auroral origin--might prove to be the source of long-standing confusion in lower-latitude TID observations.

In addition to the anticipated TID's, other types of F-layer perturbations--both previously known and, it is believed, newly discovered--were observed. The previously known ones include a type associated with geomagnetic disturbance; the newly discovered ones are of two types. The first new type resembles CW-Doppler signatures obtained on paths near the magnetic equator but with one consistent difference. The second new type consists of periodic modulation of spectral spread, with the modulation envelope having the appearance of pearl-type geomagnetic micropulsations.

The newly discovered types of F-layer disturbance seem worthy of investigation on their own, and the TID observations suggest that Homer, Alaska is an excellent site for such measurements. The TID signature recorded was similar to that obtained at middle latitudes, but the Homer results revealed two TID's that had at least 12 cycles of regular variation over at least a four-hour duration. Such persistence is not observed at middle latitudes.

It is suggested that longer-term HF-Doppler observations be conducted at Homer, concentrating on measurement of the diurnal variation of TID arrival direction. This should permit "tracking" of the midnight sector of the auroral oval around the magnetic pole if this sector is in fact a TID source region. It should also be possible to test the hypothesis that there are two distinct high-latitude source regions and probable mechanisms of TID.

**BLANK PAGE**

## II BACKGROUND AND OBJECTIVES

Remote nuclear detonations are detectable by means of the pressure perturbations they produce in the atmosphere over a great range of altitudes. Detection techniques exist that are based (1) on directly measuring pressure variations at the ground, and (2) on observing effects that propagating pressure disturbances in the non-ionized atmospheric gas produce on plasma contained in the F-layer of the ionosphere (at altitudes of a few hundred kilometers). In both these altitude regimes, a variety of natural pressure and density perturbations occur; their source and propagation characteristics are of concern because (1) they represent the geoacoustic noise background in which monitoring systems must operate, and (2) they can yield information on relevant atmospheric parameters and processes.

The research reported herein, which comprised two separate but related experiments, pertains to natural phenomena in both the above altitude regimes; the observations made, however, consisted of probing the ionosphere by radio techniques in both cases. In one case, an auroral-backscatter radar located in Homer, Alaska was used in a search for sources of Auroral Infrasonic Waves (AIW), which are detected at ground level by acoustic techniques (Wilson and Nichparenko, 1967). In the other case, the Doppler shift imposed by density variations in the ionosphere on high-frequency (HF) radio signals reflected from the F-layer was measured.

AIW's, which have been recognized for about a decade (Chrzanowski et al., 1961), are pressure waves with periods in the range of ten to one hundred seconds, associated with auroral activity. Research conducted in Alaska by Wilson (1967, 1969a, 1969b) has shown that AIW's follow supersonic motion of visual auroral forms and the electrojet

currents associated with them. Wilson interprets the AIW's as shock waves from an auroral source of infrasound. In support of his investigations into the source mechanism of AIW's, Stanford Research Institute (SRI) conducted a search in 1969 (Fremouw, 1970) for aurorally associated radar backscattering regions (i.e., radar aurora) in rapid motion that might contain AIW sources. This report describes recent, more detailed radar observations.

The earlier work showed a strong statistical relation between radar aurora--especially when in rapid motion--and AIW's. Twenty-minute to sixty-minute periods just prior to recording of AIW's by Wilson at College, Alaska were chosen for analysis of radar data collected at Homer, Alaska. This resulted in radar data for 62 AIW events; similar data were selected for 23 control periods in which AIW's were not observed. A statistical analysis was then carried out, with emphasis on radar aurora in rapid motion, which was taken to be "supersonic" if the radar revealed range variation in excess of 300 m/s.

The results of the statistical analysis were summarized in Table VI of the report by Fremouw (1970) and in the associated discussion. The salient points included observation of somewhat more radar aurora over Alaska, generally, at times of AIW activity than at other times, and considerably more radar aurora in locations along the azimuth of arrival at College AIW's than along the same azimuths during comparable control periods. More pertinent, however, was the result that supersonic motion of the radar aurora (as defined above) was seen only in the AIW-related data periods, including such motion along the AIW arrival azimuths.

The above statistical results showed that radar-auroral backscattering regions in rapid motion were related in time and general location to source regions of AIW's. They did not, however, show any one-to-one relationship that could clearly be interpreted in terms of cause and



effect. Nonetheless, it was established that supersonic radar-auroral motions and the AIW's known to follow supersonic visual aurora tend to develop in the same stages and regions of polar magnetic substorm activity. While not surprising, this result could not be assumed a priori because of the nuclear relation between visual and radar aurora and because of the lack of past work on the radar aurora in terms of substorm development.

The radar data used in the 1969 study were taken from several observing seasons at the Homer radar site, with the instrument and observing schedule set for other purposes. For the most part, the data lent themselves only to statistical study. However, a few individual events suggested that the radar may have detected auroral-backscattering plasma moving with the source of individual AIW's. It was decided, therefore, to perform observations with the radar and the observing procedure optimized for AIW-related research. It is this set of observations and the results thereof that are reported in Section III of this report.

AIW's, as a natural geoaoustic phenomenon detected at the earth's surface, represent noise or interference to ground-level monitoring systems even though their origin is in the ionosphere. Related ionospheric processes might be supposed to produce noise or interference on F-layer monitoring systems. The degree to which the noise environments in which ground-level and F-layer systems must operate are related, and the nature of any such relationship is of interest to the ARPA/AFOSR geoaoustics community (minutes of 1970 meeting).

A natural geoaoustics phenomenon of concern for F-layer systems manifests itself as Traveling Ionospheric Disturbances (TID's), which produce phase- and group-path perturbations and attendant Doppler shifts on the signals employed in such systems. TID's have been extensively

studied in many parts of the world for the past two decades. In spite of this effort, neither the source mechanisms nor the source locations of naturally occurring TID's are known. There exist many papers indicating the TID's may originate within the auroral zone, but some papers also have been published to the contrary. In addition, some suggestions have been made that TID's may be generated elsewhere--in particular, in the troposphere, where sufficient energy is available in the jet stream and the tidal or weather systems. Table 1 summarizes the suggestions that have been made on TID sources.

The evidence that TID's originate in the auroral zone is based either on a correlation of TID occurrence with geomagnetic activity, or from deductions based on apparent TID travel directions. Because most measurements are made at relatively great distances from the auroral zone, time correlations and travel directions are subject to uncertainties due to unknown velocities and measurement errors. Additionally, since observational selection by winds, by atmospheric response, and/or by equipment sensitivity may bias the measurements, conclusions based on travel directions must be interpreted with care.

Nevertheless, there exists general agreement that at least a significant portion of TID's do originate in the auroral zone and that they are manifestations of atmospheric internal gravity waves. The mode of propagation, however, whether freely propagating or confined to a leaky or fully ducted mode, is still a subject of some debate. The suggestions for specific source mechanisms are highly speculative. Suggested sources include the following: (1) a thermal process whereby the ionosphere is suddenly heated by an influx of energetic particles (Elkins and Slack, 1969; Maeda and Watanabe, 1964); (2) collisional interaction between neutral particles and ions following application of a Lorentz force  $\mathbf{J} \times \mathbf{B}$  (Piddington, 1964; Wilson, 1969a; Chimonas and Hines, 1970); and (3)

Table 1  
SUMMARY OF TID SOURCE SUGGESTIONS

Reference	Hemisphere	Observed Characteristics and Suggested Sources
Baker and Gledhill (1965)	S	Sunrise in F-region
Bowman (1965)	S	Certain auroral forms, red arcs, and VLF EM emission
Bowman (1967)	S	Radio and optical auroras and magnetic activity
Chan and Villard (1962)	N	Correlates with magnetic sudden commencement
Davis and da Rosa (1969)	N	Amplitude of electron-density fluctuations related to magnetic activity, possible relation to polar substorm
Elkins and Slack (1969)	N	Injection of energetic electrons into auroral-zone ionosphere
Georges (1968)	N	Auroral region
Goodwin (1968)	N	No correlation with magnetic storms, associated with D-region absorption
Heisler (1958, 1963)	S	No correlation with magnetic activity
Hunsucker and Tveten (1967)	N	Greater than half of events correlate with magnetic activity
Klostermeyer (1969)	N	Tropospheric source
Liszka and Taylor (1965)	N	Large irregularities correlate with magnetic and scintillation activity
Munro (1958)	S	No correlation with magnetic activity

Table 1 (concluded)

Reference	Hemisphere	Observed Characteristics and Suggested Sources
Price (1954)	S	No correlation with solar flare, auroral activity, or magnetic K indices
Thomas (1959)	N	Velocity increases with magnetic activity
Thome (1968)	N	Association with geomagnetic storm
Titheridge (1968)	S	Possible source in polar region
Vasseur and Waldteufel (1969)	N	Correlates with magnetic activity
Wright (1961)	S	Correlates with magnetic activity

heating caused by current flow about the auroral oval (joule heating) (Cole, 1962; Chimonas and Hines, 1970).

The state of understanding of TID's that originate at auroral latitudes currently is similar to the state of understanding of AIW's a few years ago. Surface acoustic noise from auroral regions was recognized for a long time on the basis of mid-latitude observations, but insight into its generation progressed much more rapidly once observations were begun within the auroral zone. It seems reasonable to hope for analogous progress from TID observations nearer to the presumed auroral source regions, and it was with this in mind that the pilot program of HF-Doppler soundings of the F-layer in Alaska, reported in Section IV of this report, was initiated.

While the HF-Doppler observations represent a self-contained experiment for study of a phenomenon of concern in its own right, they are closely related to AIW research both in application and in phenomenology. As indicated above, for application of the research reported herein, there is interest in F-layer conditions at times of surface-level geoacoustic activity and vice versa. The joint phenomenological interest in AIW's and TID's stems from the possibility that they have similar or related source mechanisms.

Judging from recent simultaneous observations at College, Alaska, and Inuvik, Northwest Territories, Wilson (private communication) believes that AIW's result from momentum transfer from ions to neutral molecules in the auroral E layer in the presence of a Pedersen current carried with supersonic visual auroral forms. Since wave energy should propagate upward from an auroral source as well as downward, TID's may be generated in a similar manner when a source region attains a suitable time and size scale. Conditions appropriate for TID generation may arise at some phase of a substorm and/or may occur in conjunction with AIW production.

Thus, the objectives of the research proposed herein were (1) to study aurorally associated radar backscattering regions (radar aurora) in rapid motion as possible sources of auroral infrasonic waves, and (2) to investigate the role of auroral activity as a possible source of traveling ionospheric disturbances. Specifically, it was proposed to conduct auroral-radar and HF-Doppler-sounder observations at Homer, Alaska during the months of October and November of 1970 and to analyze the resulting data.

The objective of the radar data analysis was to relate the position and velocity of the observed auroral forms to the source regions of AIW's observed under separate contract simultaneously at College, Alaska by the Geophysical Institute of the University of Alaska. Similarly, the HF-Doppler data were to be analyzed for speed and direction of TID's, with special regard to possible relationships with AIW's, radar aurora, and other aurorally related phenomena in Alaska.

### III RADAR SEARCH FOR SOURCES OF AURORAL INFRASONIC WAVES

#### A. Radar Operation

The instrumentation employed for this research was described in some detail in a report on the radar-AIW investigation carried out in 1969 (Fremouw, 1970). Important operating characteristics were summarized in Table 1 of that report, and block diagrams were given in Figure 2. Only the salient characteristics, as they bear on the observing program reported herein, will be discussed in this section.

Now located near Homer, Alaska, at  $59.713^{\circ}\text{N}$ ,  $151.535^{\circ}\text{W}$  (magnetic invariant latitude  $\approx 59^{\circ}$ ), the equipment was developed over a period of years at a number of sites, primarily under programs of the Defense Atomic Support Agency. Its major use has been in the study of radar clutter produced by nuclear and natural ionospheric phenomena. It is presently capable of operating at any or all of six frequencies, ranging from low VHF (50 MHz) through UHF (3000 MHz) using a common, fully steerable, 60-foot parabolic antenna for all frequencies. The antenna and the radar vans are shown in Figure 1.

For the current work, only three of the six radars were employed: those operating at 139, 398, and 1210 MHz. Pertinent characteristics of the three radars, as operated in this program, are given in Table 2. By far the greatest use was made of data from the 139-MHz radar.

The only important change in radar characteristics as compared with earlier operation was in pulse length. In the past, identical waveforms with 300- $\mu\text{s}$  pulses had been employed, yielding a range resolution of 45 km and a Doppler resolution of 3.33 kHz. In the present work, the 139-MHz radar was operated with the shortest available pulse, giving a range resolution of 12 km. This was done in order to maximize the

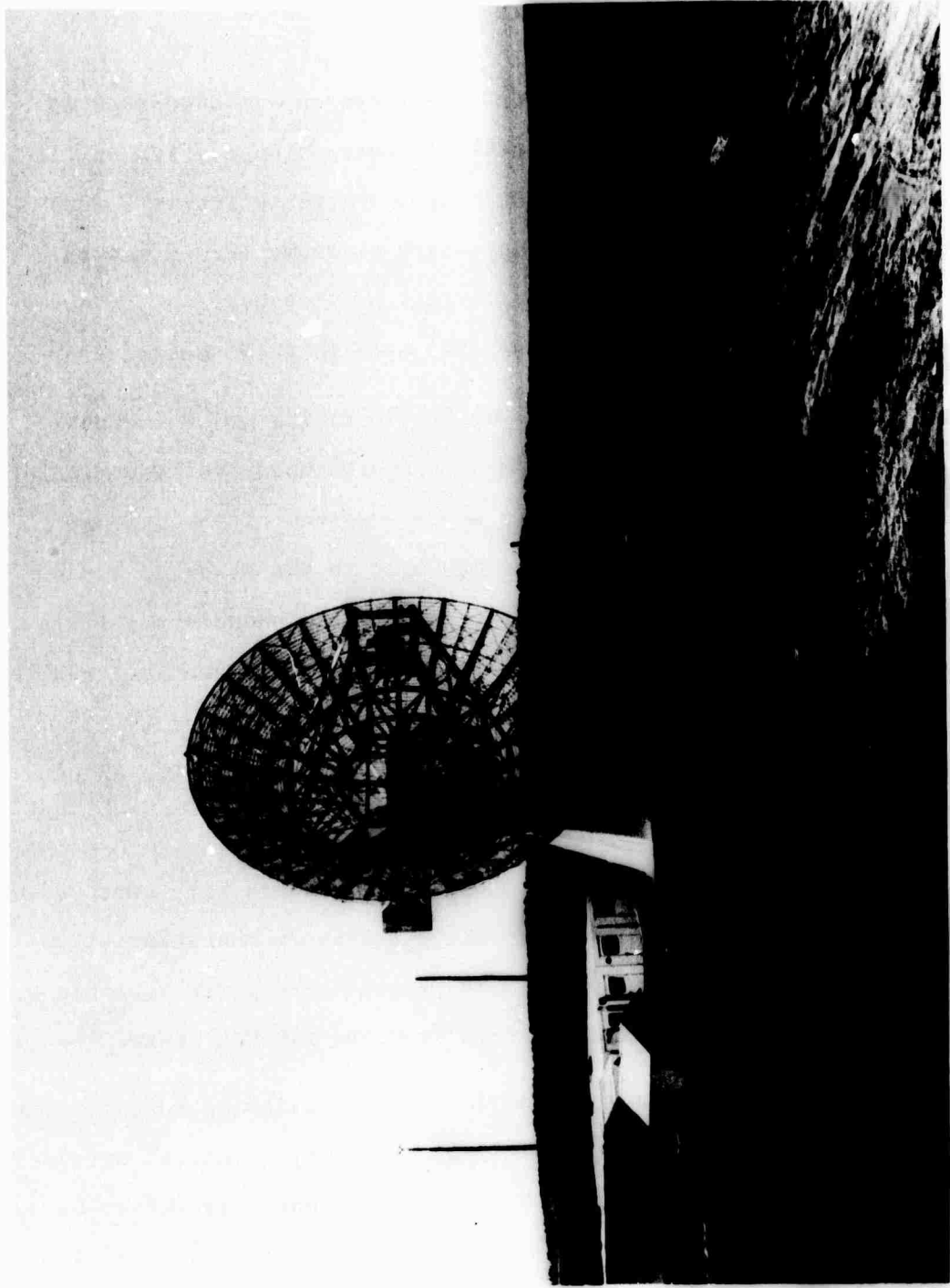


FIGURE 1 THE AURORAL RADAR ANTENNA AND VANS AT THE OHLSON MT. FIELD SITE NEAR HOMER, ALASKA



the ability to isolate individual radar-auroral forms and to measure their rate of range change, the prime type of data desired.

Table 2

PERTINENT RADAR CHARACTERISTICS

Frequency (MHz)	139	398	1210
Peak power (kW)	50	50	40
Pulse length ( $\mu$ s)	75	1000	300
PRF (p/s)	75	75	75
Antenna efficiency (%)	50	50	50
Half-power beamwidth (deg)	9	3	1
Receiver bandwidth (kHz)	26	26	26
Receiver noise level (dBm)	2	2	3
Receiver dynamic range	Approximately 80 dB		
Polarization (transmit and receive)	V	V	V

Earlier work had left little likelihood that Doppler-shift data were important for AIW purposes (Fremouw, 1970). Once the Homer site is activated, however, there is virtually no added expense and little added effort required to operate more than one radar. Therefore, the 398-MHz instrument was run, using the longest available pulse--1 ms, yielding a Doppler resolution of 1 kHz (equivalent to a Doppler velocity resolution of 377 m/s). Similarly, the 1210-MHz radar was operated as a monitor on intense radar-auroral activity, since the strength of return from a given aurora decreases with increasing observing frequency. Returns were seen at 1210 MHz on a number of occasions during the observing period.

In the earlier work (Fremouw, 1970) it had been found that a complete mapping of radar aurora over Alaska was seldom feasible on the time scale needed for AIW research. Such mapping has often been done

in the past by scanning the antenna in a grid pattern of azimuth and elevation, but such an "all-sky scan" takes several minutes. During such a period, the rapidly moving forms of interest for AIW research change location and shape significantly. Only in fortuitous circumstances was it possible to obtain a useful velocity measurement on such forms in the "all-sky-scan" mode of operation. [See, for instance, Figure 13 and the associated discussion in the report by Fremouw (1970)].

On the other hand, the earlier work suggested that measurement of one velocity component--i.e., range rate--with the antenna fixed at a preselected position of interest might lead to identification and pertinent information about radar auroral sources of AIW's. [See, for instance, Figure 14 and the associated discussion in the report by Fremouw (1970)]. Thus, the mode of radar operation used in the present work was essentially the fixed-antenna mode.

Figure 2 shows the observing geometry in plan view. Auroral radar echoes result from backscattering by structure in aurorally disturbed E-layer ionization. The plasma structure of importance is that having a scale in the range dimension on the order of the radar wavelength and is found empirically to be elongated along the geomagnetic field. The field alignment results in strong aspect sensitivity of the strength of the radar returns, with the strongest and most frequent echoes being received from auroral plasma located where the radar beam intersects the geomagnetic field within a few degrees of perpendicularity. Contours of zero- and one-degree off-perpendicularity are shown in Figure 2 for observations from Homer of the 110-km level.

The circle in Figure 2 centered on the location of College, Alaska represents the region covered with good accuracy at the 110-km level by an auroral all-sky camera. An intersecting arc, centered on Ft. Yukon, Alaska shows the region jointly covered by the College and Ft. Yukon

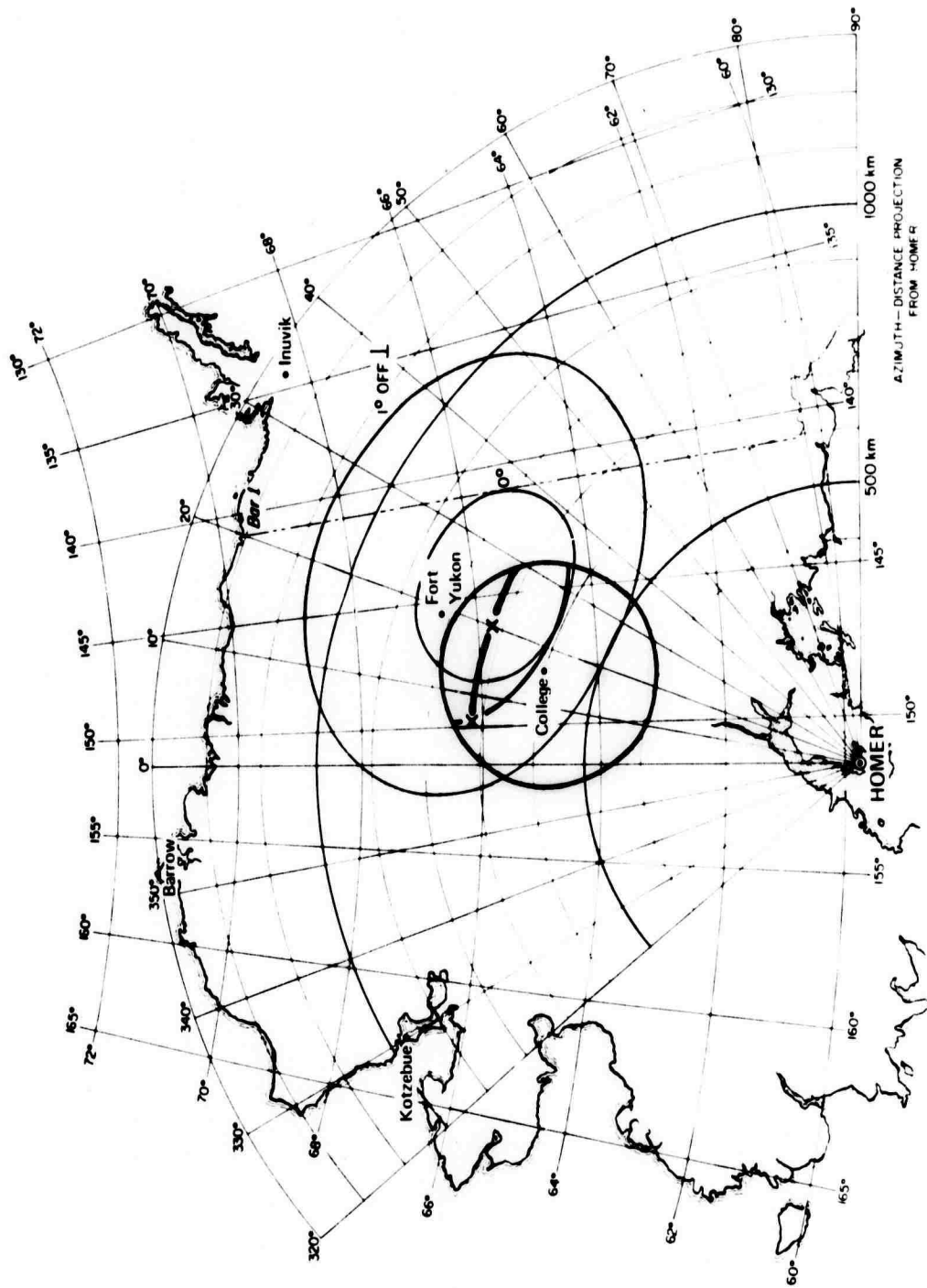


FIGURE 2 PLAN VIEW OF OBSERVING GEOMETRY OVER ALASKA FROM THE HOMER RADAR

all-sky cameras. Superimposed on the figure, in the jointly covered region, is a bolder arc, centered on Homer, that represents the intersection of the radar beam center with the 110-km level for an antenna elevation angle of  $6^{\circ}$ . This arc lies (at the 110-km level) at a magnetic invariant latitude of approximately  $66^{\circ}$ , a region of considerable visual and radar auroral activity during nighttime hours.

During the local nighttime hours corresponding to 0900 to 1700 UT (2300 to 0700 AST), the preferred arrival azimuth of AIW's observed at College progresses from about  $40^{\circ}$  through north to about  $335^{\circ}$ . For radar observations at  $6^{\circ}$  elevation from Homer, this corresponds to a westward progression of radar azimuth, between the two X's shown in Figure 1, at about  $2^{\circ}$  per hour.

A radar observing schedule was used that sought to take advantage of (1) the fixed-antenna radar mode, (2) the strong auroral-radar echoes obtainable from a region of near-magnetic perpendicularity at a magnetic latitude of  $66^{\circ}$ , (3) the possibility of simultaneous all-sky-camera data on the visual aurora from College and/or Ft. Yukon, and (4) the known morphology of AIW activity. It consisted of activating the radar at about 0900 UT, with the antenna set at  $6^{\circ}$  elevation and  $20^{\circ}$  azimuth, and then changing azimuth only in  $2^{\circ}$  increments on each hour. Observations usually were terminated at an azimuth between  $8^{\circ}$  and  $6^{\circ}$ , between 1500 and 1700 UT. (In a few instances of sustained activity, observations were continued beyond 1700 UT.)

Between azimuth changes, the antenna was left fixed about 90 percent of the time, being moved only for brief elevation scans between  $0$  and  $10^{\circ}$  at about five-minute intervals for the purpose of periodic checks on latitudinal extent of the radar aurora. Figure 3 shows the observing geometry in the elevation plane, including the altitude regime of the large majority of radar aurora and the half-power beamwidths of the 139- and 398-MHz radars. It can be seen that, at such a low elevation angle

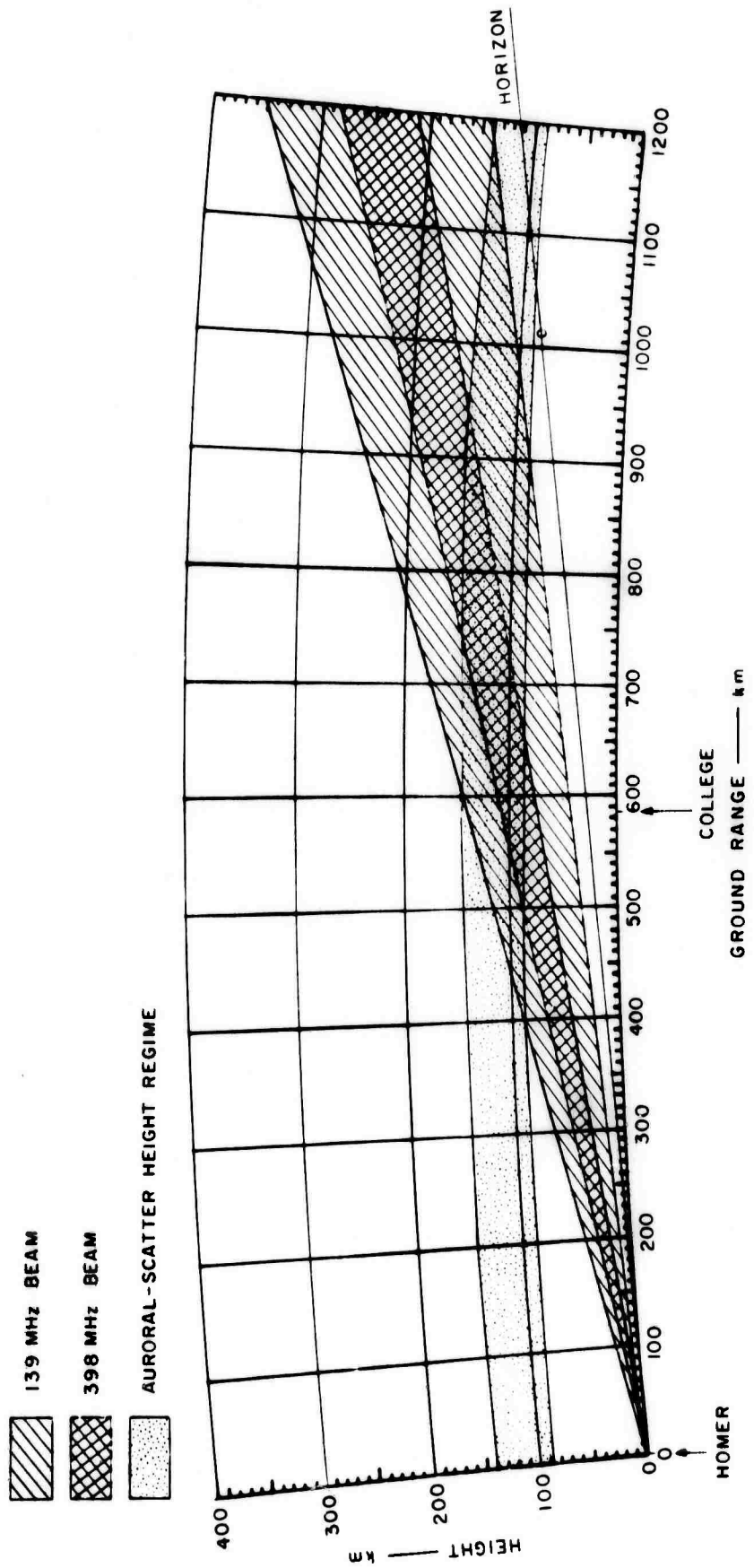


FIGURE 3 RADAR OBSERVING GEOMETRY IN THE ELEVATION PLANE

as  $6^{\circ}$ , a range measurement is tantamount to a measurement of horizontal distance, but that the region of sensitivity to radar aurora is increased by scanning in elevation angle.

Radar operation according to the above schedule began on 13 October 1971 and terminated on 23 November 1971.

#### B. Data Handling

For the range-rate measurements desired for comparison with AIW data, the format used consisted of film records of radar-auroral intensity vs. range and time (Range-Time-Intensity, or RTI, records). These are commonly used in many radar studies and are obtained, in the present case, from analog tape recordings of successive A-scans (records of the intensity of the returned radar signal vs. delay time, which corresponds to target range). The recordings made at the Homer site are of both the predetected (Intermediate-Frequency, or IF) signal and the detected (video) signal, on separate recorder channels. Other tape channels contain time, antenna-position information, and a synchronization signal.

Two types of RTI records were produced for this program. First, a complete set of "quick-look" records was run, as is standard practice with all data from the Homer radar. The quick-look records are obtained by playing back the video signal into a Granger Associates Model 9190 electrostatic printing recorder. The Granger recorder acts essentially as an oscillograph, with the radar video signal performing "z-axis," or intensity modulation. Successive A-scans are recorded side by side across the chart by an electrostatic printing process, as recorder paper is continually advanced to produce the time axis.

These inexpensive quick-look records are used for data editing and are then photographed in groups for a continuing catalog of Homer data. Figure 4 is a reproduction of a data-catalog page, containing quick-look

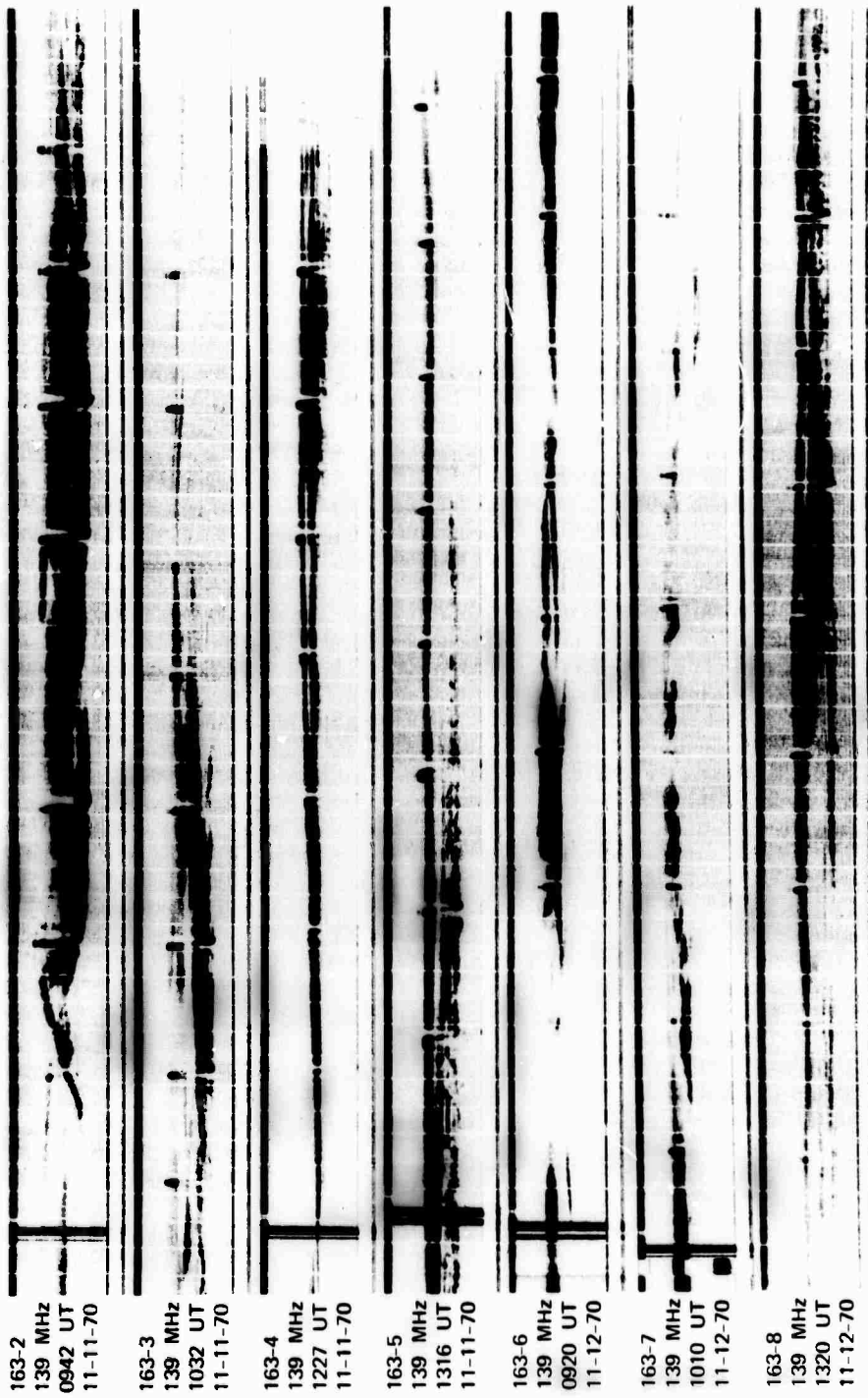


FIGURE 4 SEVEN EXAMPLES OF QUICK-LOOK, RANGE-TIME-INTENSITY (RTI) RECORDS

records of 139-MHz radar aurora from seven data tapes, each of about 50 minutes duration. The records cover a range extent from the radar out to 1500 km, which coincides with the beginning of the calibration pulse (the dark horizontal band along the top of each record). Time is indicated by minute marks, which appear as vertical lines across the records; start time and date are indicated at the beginning of each record, along with frequency and tape identification number.

The pattern that recurs on the records, usually at intervals of five minutes, results from moving the antenna in an elevation scan from its otherwise fixed position. The elevation scans often show some radar aurora to the north of that detected with the antenna fixed, but seldom show any to the south. The quick-look records are useful for obtaining a synoptic view of radar-auroral activity and for locating unusual events. An event of interest, for instance, is the auroral form seen to recede from the radar (slope upward on the record) for several minutes near the beginning of the first record in Figure 4 (#163-2); we shall return to this type of event in Section III-D.

The primary goal for analysis of the RTI data was to determine if individual sources of AIW's could be identified in the radar aurora. To this end, some experimentation in data handling was carried out. Of prime interest was preservation of detailed structure in the records of radar echo strength vs. range. It was found that details of this structure sometimes were distorted by slight "ringing" in the electronics associated with the video-data, tape-recorder channel. In a departure from past procedures, therefore, the broader-band IF channel, usually used only for Doppler analysis, was used.

After comparison of results from slightly different approaches to handling the IF data, a very simple procedure was adopted. The recorded IF signal was used directly to intensity-modulate an oscilloscope, which effectively detected the signal, with the scope triggered from the



recorded sync signal. An attached camera was then used to photograph the scope face, with the film continually moving as successive intensity-modulated A-scans were displayed.

The dynamic range of the oscilloscope/film combination is greater than that of the Granger electrostatic printing paper, but it still is insufficient to display the entire range of radar-auroral intensity recorded. Various electronic and photographic adjustments were used to permit detailed study of individual auroral features of interest. The study was performed by visual inspection of 70-mm film on a light table. Photographic prints of two such film strips in the format actually used appear in Figure 5.

The combination of shorter transmitted pulse and the use of the IF-signal and film format for data processing resulted in considerably better range and time resolution than was previously available in Homer radar RTI records. The use of 70-meter film at the rate of 318 mm per minute of elapsed observing time, as in Figure 5, also increased a viewer's sensitivity to range change.

### C. Results Concerning AIW Sources

The data analysis was essentially a search for a distinctive feature in the auroral radar RTI records, described in Section III-B, that could be identified as the hallmark of an AIW source. Its prime characteristic should be rapid and sustained change in range. The most recent AIW observations of Wilson (private communication) have been performed simultaneously at College, Alaska, and Inuvik, Northwest Territories. (See Figure 2 for locations.) The salient conclusion from these two-station observations, for present purposes, is that the AIW sources move southward toward the Homer radar and not northward away from it.

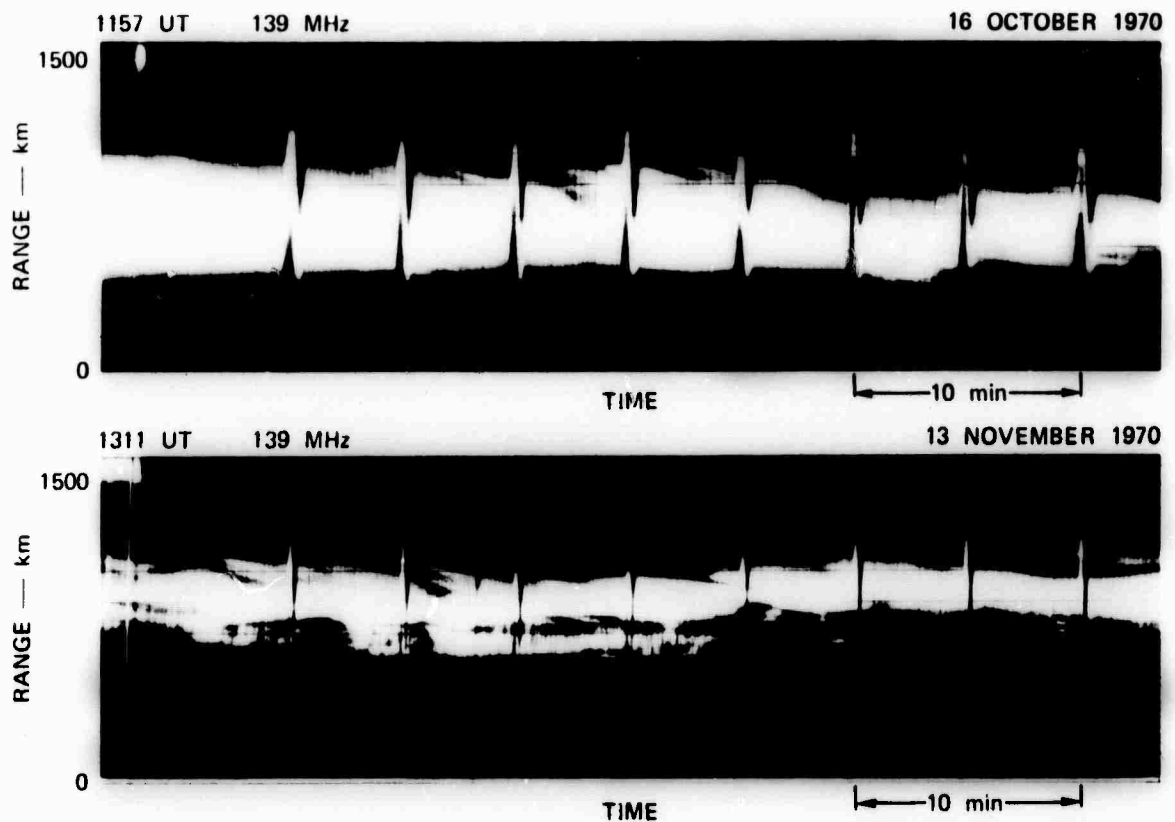


FIGURE 5 TWO EXAMPLES OF RTI RECORDS USED IN DETAILED ANALYSIS

For the six-week radar observing period, data were obtained from Wilson (private communication) for 76 AIW's that were recorded at College. Of these, 41 occurred during periods when radar data were being recorded. For these 41 events, available auroral and AIW data were assembled. AIW scalings were obtained from Wilson at the University of Alaska, and the corresponding radar data were edited by means of the "quick-look" records. In addition, visual auroral data in the form of all-sky-camera films from College and magnetic-disturbance data in the form of College magnetograms were obtained from Wilson. Table 3 is a tabulation of the assembled data, except for the magnetograms, which were available for all events.

Table 3

## AVAILABLE AIW AND AURORAL DATA

AIW Data			Radar Data			All-Sky-Camera Data
Event No.	GMT Date	GMT	Tape No.	Start (GMT)	End (GMT)	Comments
4	16 Oct	1025	159-5	0948	1036	Aurora through clouds
6	16 Oct	1222	159-7	1157	1245	Cloudy
7	16 Oct	1243	159-7	1157	1245	Cloudy
11	17 Oct	1211	159-11	1131	1220	Cloudy
12	17 Oct	1316	159-12	1227	1315	Cloudy
13	17 Oct	1358	159-13	1319	1408	Cloudy
15	18 Oct	0859	159-19	0857	0945	Cloudy
16	18 Oct	0944	159-19	0857	0945	Cloudy
19	22 Oct	0944	160-9	0937	1028	Cloudy
20	22 Oct	0956	160-9	0937	1028	Cloudy
21	22 Oct	1110	160-10	1034	1120	Cloudy
22	22 Oct	1132	160-11	1125	1212	Cloudy
23	22 Oct	1148	160-11	1125	1212	Aurora through clouds
24	22 Oct	1157	160-11	1125	1212	Aurora through clouds
26	22 Oct	1422	160-12	1348	1435	Cloudy
27	22 Oct	1430	160-12	1348	1435	Cloudy
28	22 Oct	1440	160-12	1348	1435	Cloudy
35	23 Oct	1048	160-14	1003	1049	No data
36	24 Oct	1201	160-20	1159	1246	Aurora through clouds
43	5 Nov	1625	161-19	1550	1636	Cloudy
46	6 Nov	0958	161-20	0954	1041	No data
47	6 Nov	1141	161-21	1043	1131	No data
48	6 Nov	1223	161-22	1133	1220	No data
50	7 Nov	0933	162-3	0921	1008	Good data
51	7 Nov	1071	162-4	1010	1057	Good data
54	7 Nov	1026	162-4	1010	1057	Good data
55	7 Nov	1020	162-4	1010	1057	Good data
56	7 Nov	1118	162-5	1101	1148	Good data
57	7 Nov	1124	162-5	1101	1148	Good data
58	7 Nov	1204	162-6	1151	1238	Good data
59	7 Nov	1210	162-6	1151	1238	Good data
60	7 Nov	1415	162-8	1333	1421	Good data

Table 3 (concluded)

AIW Data			Radar Data			All-Sky-Camera Data
Event No.	GMT Date	GMT	Tape No.	Start (GMT)	End (GMT)	Comments
61	7 Nov	1420	162-8	1333	1421	Good data
62	7 Nov	1426	162-9	1424	1511	Good data
63	7 Nov	1438	162-9	1424	1511	Good data
64	7 Nov	1448	162-9	1424	1511	Good data
65	7 Nov	1538	162-10	1513	1601	Good data
69	13 Nov	1348	163-10	1311	1359	Cloudy
70	18 Nov	1456	163-25	1409	1457	No data
71	18 Nov	1510	164-1	1500	1545	No data
72	18 Nov	1518	164-1	1500	1545	No data

There was no attempt or need to repeat the statistical study of the AIW/radar-aurora relationship carried out earlier (Fremouw, 1970). For purposes of event selection for detailed data comparison, however, maps were made of AIW arrival direction and radar-beam location. An example is shown in Figure 6, where the straight line terminating at College represents the measured arrival azimuth of the AIW's and the box enclosing College and Ft. Yukon represents the approximate half-power coverage pattern of the 139-MHz radar at E-layer heights. The situation shown in Figure 6 is quite representative of the coincident coverage obtained from the observing routine described in Section III-B.

Auroral echoes were present on all the radar data tapes listed in Table 3 in the period just prior to AIW reception, except in one case. Generally speaking, the radar aurora in these periods was rather extensive and strong. The one case in which no echo was received turned out also to be the one case in the entire data collection in which the radar was "looking in the wrong direction." That is, it was the one case in which the AIW arrival line did not enter the radar coverage pattern (as illustrated in Figure 6) at all. This resulted from an unusual early-morning (1625 UT) AIW arriving from the northeast, while the radar was aimed to the north and west of College in accord with statistical expectation of AIW arrival direction.

The consistency with which radar aurora was observed prior to AIW arrivals at College vindicates the radar-aiming routine used. At the same time, this consistency and the one exception to it described above reinforce the statistical result from the earlier study that bright and extensive radar aurora is strongly related in at least a general way to AIW activity, even though no synoptic type of study was performed in the present program. That is, AIW's occur at times of, and arrive from directions of, strong radar auroral activity.

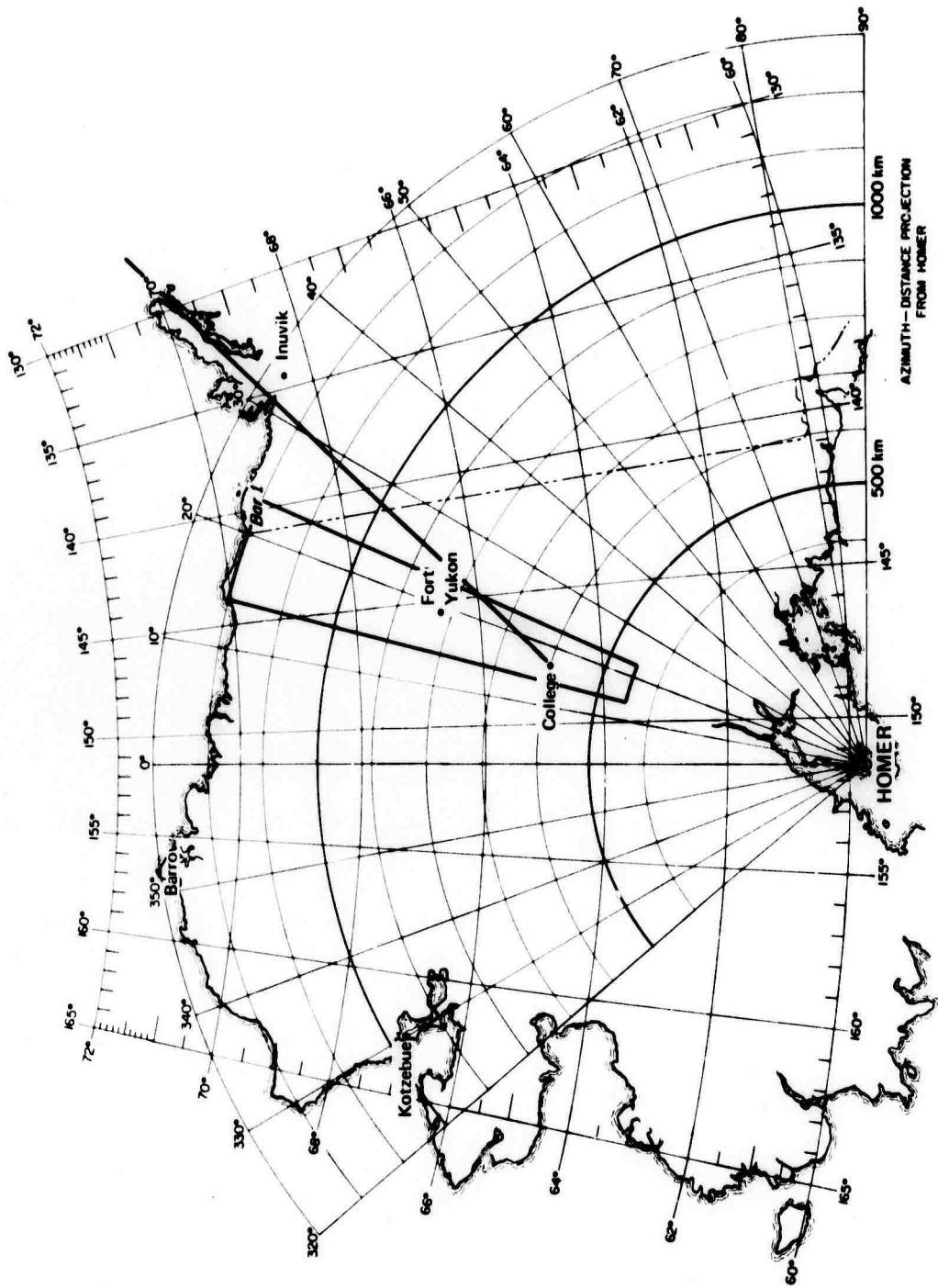


FIGURE 6 MAP DEPICTING EXAMPLE OF COINCIDENCE BETWEEN RADAR COVERAGE AND PATH OF AN AIW ARRIVING AT COLLEGE, ALASKA

Turning now to the search for an AIW signature in the auroral radar records, the first approach was to use only the AIW and radar data, without resorting to the supporting all-sky-camera observations. A few events in Table 3 were excluded on the basis of editing the "quick-look" radar records. These included events for which radar observations were interrupted by tape changes in the period just prior to AIW recording, and events in which the radar aurora was too "solid" in range extent to permit identification of structure that could be regarded as individual forms or features. For the remaining events, the radar IF signals were used to produce RTI records on film, of the type shown in Figure 5.

The film RTI records were scanned visually in the hope of finding a distinctive AIW signature--i.e., a repeatable feature associated with AIW reception at College that would stand out clearly on the records. Again, the expected characteristic of such a feature would be that it would move rapidly toward the radar--presumably at a speed noticeably greater than similar features not associated with AIW and at a speed that could be identified as supersonic in the auroral E layer.

Figure 7 (top) shows two distinctive developments in the 139-MHz radar aurora having the characteristic described above. The developments consist of strongly backscattering regions moving out of the north from a region of more stationary radar aurora and approaching the radar at high velocity, as indicated by the large slope of the echoes in the range-vs.-time plane. The development on the right-hand end of the record shows the higher closing speed, with the leading edge approaching the radar at about 1200 m/s. This velocity was sustained for more than two minutes, with the echoing region moving well over 150 km.

The horizontal arrows at the ends of the radar record in Figure 7 indicate the range of the College zenith from Homer at an altitude of

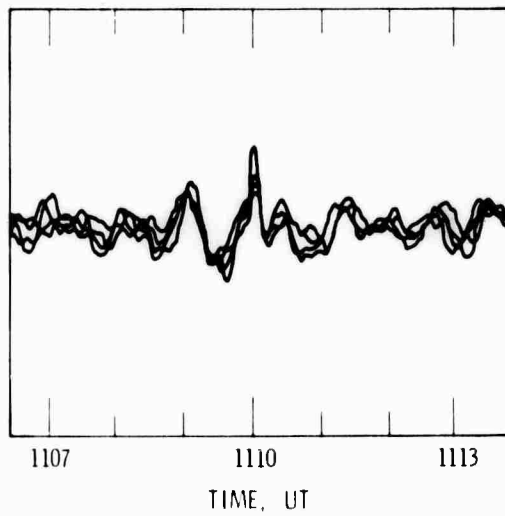
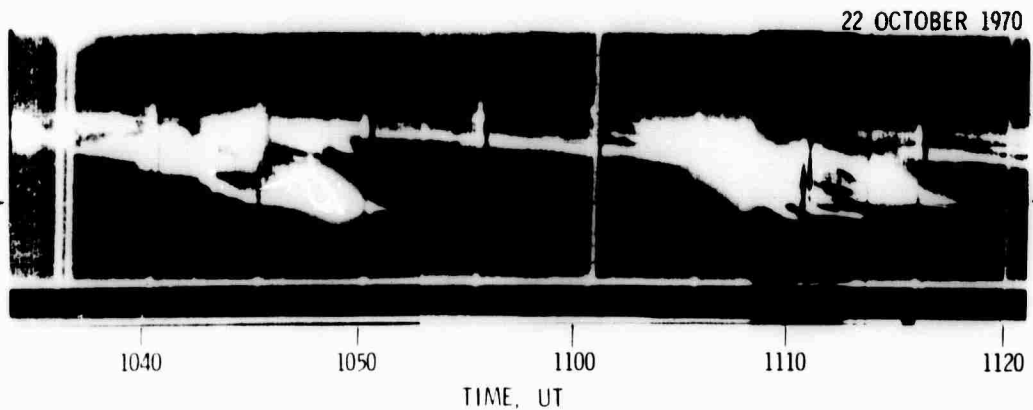


FIGURE 7 TWO DISTINCTIVE RADAR-AURORAL DEVELOPMENTS (top) AND AN AIW FOLLOWING ONE OF THEM (bottom). Arrows denote range of the College zenith.



110 km. The rapidly approaching feature of interest reached this range some seconds before 1108 UT. Wilson's list of AIW's included one that arrived at the nominal time of 1110 UT; the infrasonic record of this event is shown in Figure 7 (bottom). The record consists of superimposed traces from three microbarographs, with the AIW's represented by the existence of coherent oscillations in the three traces, peaking at 1110 UT.

Although one might have expected a slightly greater time delay between passage of the radar auroral form over College and arrival of the AIW's, nonetheless the sequence of events described above, on its own, is an encouraging one in the search for an auroral-radar signature of AIW's. However, the similar radar-auroral development between 1040 and 1050 UT negates this encouragement. In this earlier development, the leading edge approached at about 800 m/s, with this speed again sustained for over two minutes. Again, the form reached the range of the College zenith, with the radar beam illuminating the E-layer over College. However, no AIW was reported by Wilson until the one at 1110 UT, about 24 minutes later.

Inspection of the other film RTI records produced similarly inconclusive results. A number of radar-auroral features were found to move toward the College zenith in the periods preceding AIW reception at College. These features were not unique, however, with similar motions taking place that were not followed by AIW's. (It should be borne in mind here that all records used were selected on the basis of AIW occurrence. The statement above means that one-to-one identifications of radar-auroral forms as AIW sources were not made; it is not inconsistent with earlier statistical findings that the two phenomena tend to occur together.)

With only inconclusive results from the two-way comparison between radar and AIW data, the next step was to appeal for support to the all-sky-camera films. The approach here was to find supersonic visual forms thought to contain the source of an observed AIW and then to search for a feature on the radar records that appeared to be associated with the visual form. Figure 8 shows an informative result of this search, from data taken on 7 November 1970, UT.

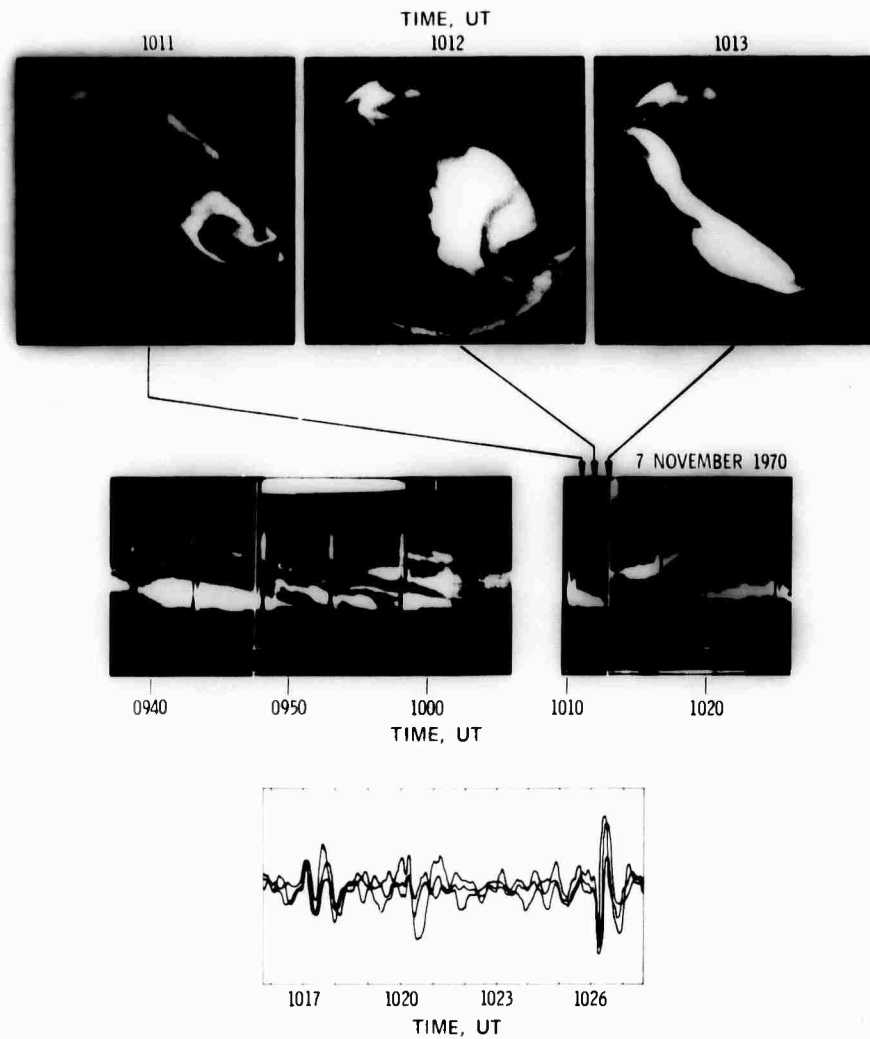


FIGURE 8 COMPARISON OF VISUAL-AURORAL DEVELOPMENT (top), RADAR-AURORAL DEVELOPMENT (center), AND AIW RECORD (bottom)

On the bottom of Figure 8 are shown three superimposed microbarograph traces from the College array. They reveal three AIW's, with the traces overlaid to match best during the center event, which began at about 1020 UT. The other AIW events, which can be seen readily, began at about 1017 and 1026 UT, respectively. Wilson suggests that these three AIW's probably resulted from passage over the College zenith of the auroral westward surge shown in the three all-sky-camera photographs at the top of Figure 8. The first two AIW's probably were direct shocks from the complicated supersonic auroral form, and the third, which has a negative-pressure first half cycle may be a reflected shock from the same form.

In the center of Figure 8 is shown the radar-auroral development before, during, and after the AIW activity. Unfortunately, the radar tape was changed during the time-period shown, resulting in about a three-minute break in the record. Nonetheless, it is clear that at the time at which the visual westward surge passed over College, the Homer radar was receiving auroral echoes from the range of the College zenith (as demarked by the arrows at the ends of the radar record).

Close inspection shows that the radar auroral form in question was approaching Homer from beyond College and thus had a southward component of motion toward College, as did the "westward" surge of visual aurora. (It should be noted that geomagnetic north is at the top of the College all-sky-camera frames and that the radar beam also was directed approximately along the College magnetic meridian at the time of these observations.) The radar auroral form can be traced back across the record break and identified as moving toward the south over a period of about ten minutes, at about 400 m/s as measured from the slope on the RTI record.

It seems very likely that the radar-auroral feature described above was related to the visual auroral feature that passed supersonically over

College as a westward surge and to the AIW that followed. However, it is hardly a unique or striking feature on the RTI record. Several similar features can be seen on the earlier record strip, generally approaching the radar and reaching the College zenith, with no ensuing AIW.

This general southward motion does not seem to persist after the westward surge of visual aurora at about 1013 UT, with the radar aurora near College dissipating thereafter. The next prominent radar auroral form is at a greater range than the College zenith and moving northward. We shall return to similar radar-auroral developments in Section III-D.

Figure 9 shows a comparison of visual and radar auroral data and another AIW record, again from the night of 7 November, when the sky was clear at College and there was considerable activity. The combination of 35-mm data from an SRI-developed all-sky camera utilizing a fish-eye lens, operated by the University of Alaska, and the 70-mm RTI data from the Homer radar utilizing a 70- $\mu$ s pulse, has proved to be very useful for detailed comparisons, as contrasted with data available in the past.

Figure 9 again shows identifiable radar-auroral forms moving toward Homer from beyond College and enveloping the College zenith at times when the College all-sky camera was recording overhead visual aurora that was followed by AIW reception. Again, however, the radar-auroral features do not stand out as obviously significant ones on their own. It is only with the aid of the all-sky camera that they can be identified as probably related to individual AIW's, as in the sequence just before 1120 UT, leading to the AIW just after 1124 UT.

Sometimes the radar can support the all-sky camera, in a complementary manner, as in the case of the AIW at 1118 UT. In this case, no obvious visual auroral form moving supersonically was found on the College all-sky-camera film, but the Homer radar did record sustained southward motion from north of College, with the edge of an identifiable feature reaching

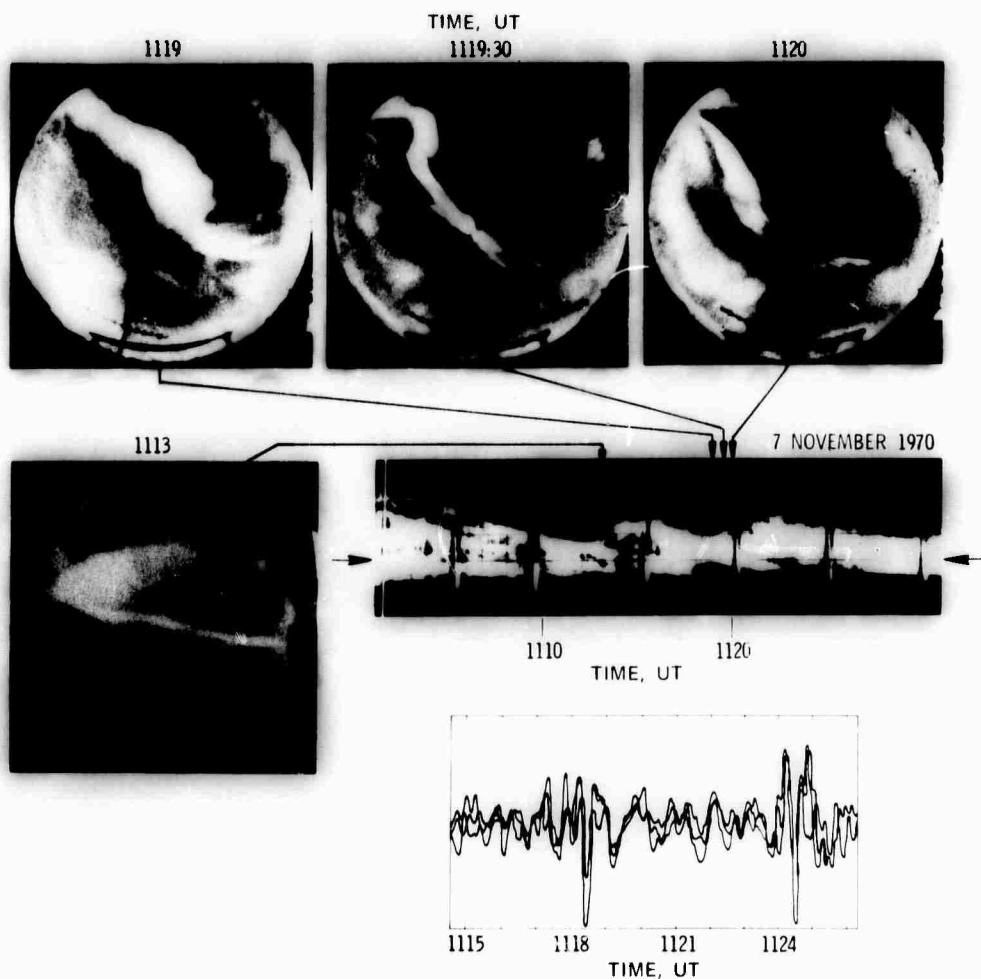


FIGURE 9 ANOTHER COMPARISON OF VISUAL-AURORAL, RADAR-AURORAL, AND AIW DEVELOPMENTS

the range of the College zenith at about 1113 UT. As pointed out above, such features on the fixed-antenna RTI records are not always followed by AIW, however, and cannot be uniquely identified as the radar signature of AIW.

The difficulty is that under the aurorally active conditions in which AIW's occur, fixed-antenna RTI records much of the time show southward motion in the radar aurora, and much of this motion appears on such records to be "supersonic" (range-rate of 300 m/s or greater), or nearly so. This very likely results from a geometric effect, at least

in part, as can be seen by referring to Figures 2 and 6 and to the all-sky-camera photographs in Figures 8 and 9.

The all-sky-camera photographs are dominated by bright auroral forms having quasi-arclike structure that stretches essentially across the frames. Comparison of the size of the all-sky-camera field and the antenna beamwidth at the range of College, from Figures 2 and 6, respectively, shows that such arc-like forms would stretch entirely across the radar beam. For an arc-like backscattering region with such a shape, tilted relative to the geomagnetic meridian and moving approximately normally to its own extent, as are the auroral forms in the all-sky photographs, the radar would record a range rate larger than the forward velocity of the region, since the antenna beam is directed essentially along the magnetic meridian.

Referring to Figure 6, one can see that such an extended form moving across the beam would result in a range rate that is greater than its forward velocity by a factor equal to the secant of the angle,  $\theta$ , between the forward-velocity vector and the beam-alignment direction. The geometrical effect is the same as that for a water wave striking a breakwater. In addition, the range depth of such a region, measured with the radar, would be greater than its transverse thickness by the same factor.

When the near end of such an extended but finite backscattering region enters the beam, the range-rate of the leading edge of the echo will suddenly drop to the radial component of the forward velocity (i.e., by a factor of  $\cos^2 \theta$ ), while that of the trailing edge will persist as before. The range extent of the echo will decrease until the backscattering region leaves the beam, producing a wedgelike pattern on the RTI records. Details of the pattern, of course, would be affected by the actual shape of the backscattering region and weighted by the radar beamshape, but such a sequence of events is sometimes suggested

by patterns on the RTI records. For instance, see the radar-auroral development between about 1105 and 1115 UT in Figure 7. Other developments on the same record also contain some of the described features.

On the basis of the discussion and figures in this section, it is suggested that a VHF or UHF radar is, in fact, capable of detecting backscattering plasma containing AIW sources, but that a more sophisticated instrument than the present Homer radar would be necessary for isolating and clearly identifying them. Geometrical effects attendant to the fixed-antenna mode of operation, as described in the foregoing discussion, result in range rates that can suggest supersonic radar-auroral motions even when the backscattering forms are moving subsonically. This accounts for the excess of apparent supersonic forms as compared with recorded AIW.

On the other hand, only fortuitous circumstances permit more complete and accurate description of fast-moving radar-auroral forms by antenna scanning, as was found in earlier work (Fremouw, 1970). We shall return to these matters in Section V, turning now to a more definitive and unexpected result of the present research.

#### D. Auroral-Substorm Radar Signature--An Unexpected Byproduct

In addition to the AIW, all-sky-camera, and radar data, inspection was made of some College magnetograms, since it is known that AIW sources are accompanied by auroral electrojet currents that produce recognizable magnetic perturbation patterns (Wilson, 1969b). In the course of comparing the radar RTI records and the magnetograms for 22 October 1970, an interesting sequence of events was noticed.

The two rapid southward excursions of radar aurora shown in Figure 7 and discussed near the middle of Section III-C were preceded by a similar excursion, in which the radar aurora did not quite reach the range of the College zenith as in the two later events. These three

excursions were each accompanied by an identifiable magnetic perturbation, as can be seen on the magnetogram shown in Figure 10. (The radar record shown in Figure 7 is reproduced also at the top right of Figure 10, for convenience.)

The magnetic perturbations of interest are most readily seen on the declination (D) channel as three prominent positive spikes, two between 1000 and 1100 UT and one after 1100 UT. Careful inspection of the other two magnetogram traces shows coincident spikes, negative in the vertical component (V) and positive in the horizontal component (H). A similar magnetic event seems to have occurred near 0930 UT, but the radar had not yet been activated for the night at that time.

Turning attention to the radar records in Figure 10, it is seen that radar-auroral motion was generally toward the radar in the top strip, including the two rapid southward excursions, and on into the bottom strip until about 1136 UT. From that time on, the character of the radar aurora is decidedly different, with the new phase being abruptly initiated by a bright form moving rapidly away from the radar.

At the same time, the geomagnetic field as measured on the College magnetogram also enters a new phase of disturbance. The onset of the new phase is marked by a negative excursion in D, a less rapid positive excursion in Z, and an abrupt beginning of a negative bay in H. These sudden changes in the geomagnetic field at College coincide with passage of the northward-moving radar-auroral form across the College zenith. The range rate of this form is about 2 km/s, and the abrupt change in H measures about 180  $\gamma$ .

The sky was overcast at College on the night in question, but at the time of this event visual aurora was recorded through the clouds for a few minutes with the College all-sky camera. The event appears to correspond to an explosive phase of auroral development.



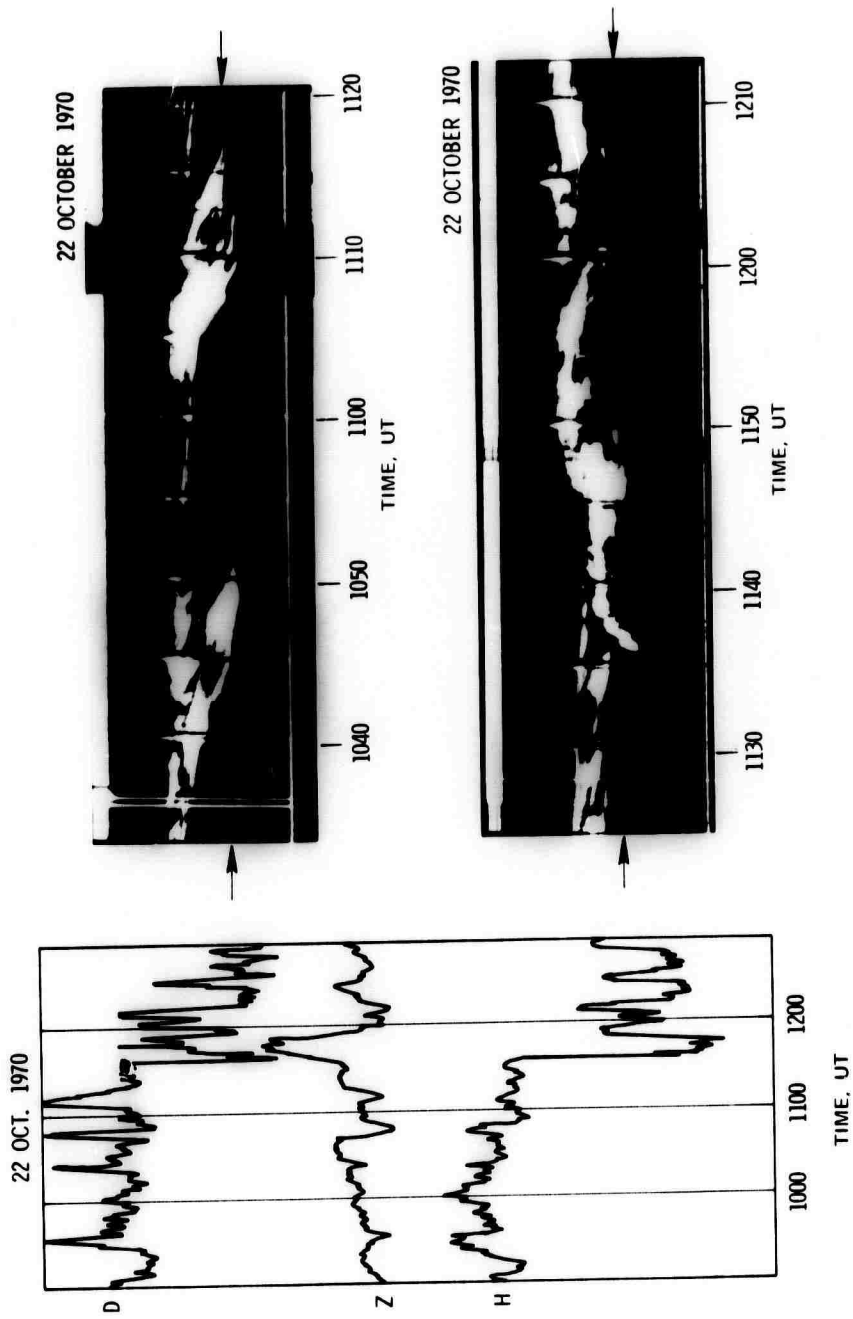


FIGURE 10 COMPARISON OF COLLEGE MAGNETOGRAM WITH HOMER RADAR RTI RECORD SHOWING THREE DISTINCTIVE DEVELOPMENTS (two rapid southward motions and one rapid northward motion)

After the event described above was noted, the quick-look radar records were inspected for other cases of prominent radar auroral forms in rapid motion away from the radar. Two other examples were found, one of which appears near the beginning of the top record strip in Figure 4. The IF recordings from the 139-MHz radar were used to produce film RFI records for these events, as shown in Figure 11. The lower record corresponds to the top quick-look strip in Figure 4, obtained from data recorded on 11 November 1970, and the upper record contains an event observed on 16 October 1970.

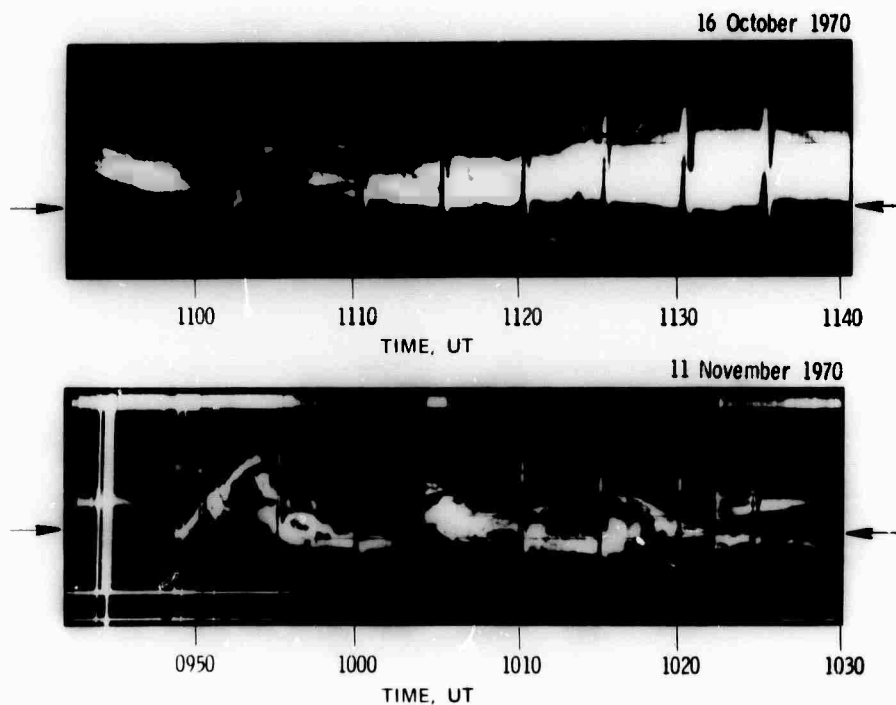


FIGURE 11 TWO MORE EXAMPLES OF DISTINCTIVE RADAR-AURORAL FORMS MOVING RAPIDLY NORTHWARD (beginning about 1102 on the top strip and about 0949 on the bottom strip)

The magnetograms for 16 October and 11 November were examined and found to contain negative bays in H, starting at 1102 and 0949 UT, respectively. These times correspond very closely to the times at which the rapidly moving radar auroral forms were at the range of the College zenith, as shown by the arrows at the ends of the records in Figure 11. The 16 October form moved northward at about 2 km/s in range rate, and the 11 November form moved out in range almost 600 km in five minutes at an average range rate of just under 2 km/s.

As was the case on 22 October (event of Figure 10), the sky was overcast at College on 16 October, but again visual aurora was recorded through the clouds by the College all-sky camera for a few frames during the northward motion of the radar auroral form. On 11 November, the sky was clear; the all-sky camera recorded bright aurora moving northward over the College zenith at the time in question. The visual aurora was undergoing development typical of the poleward expansion phase of an auroral substorm.

With three events of the type described above identified, it became possible to find others by looking at the all-sky-camera films or the magnetograms first, instead of at the radar-auroral records. An example of an event found first by noting a poleward expansion on the all-sky-camera records is shown in Figure 12. The all-sky camera frames at the top of the figure clearly show visual aurora emerging from south of College and passing over the zenith at about 1042 UT on 7 November 1970. The magnetogram in the lower right shows a negative bay of about 900  $\gamma$  beginning at the same time, and the RTI record shows a radar-auroral form moving northward across the College zenith at about 800 m/s.

It is clear now that what has been discovered in the events described above is the radar signature of the poleward-expansion phase of polar magnetic (or auroral) substorms. Seven such events have been identified

in the radar data from the six-week observing period in October and November of 1970. In addition to the four shown in Figures 10, 11, and 12, such signatures have been found at 1239 on 6 November, 0933 on 9 November, and 1127, on 23 November, UT.

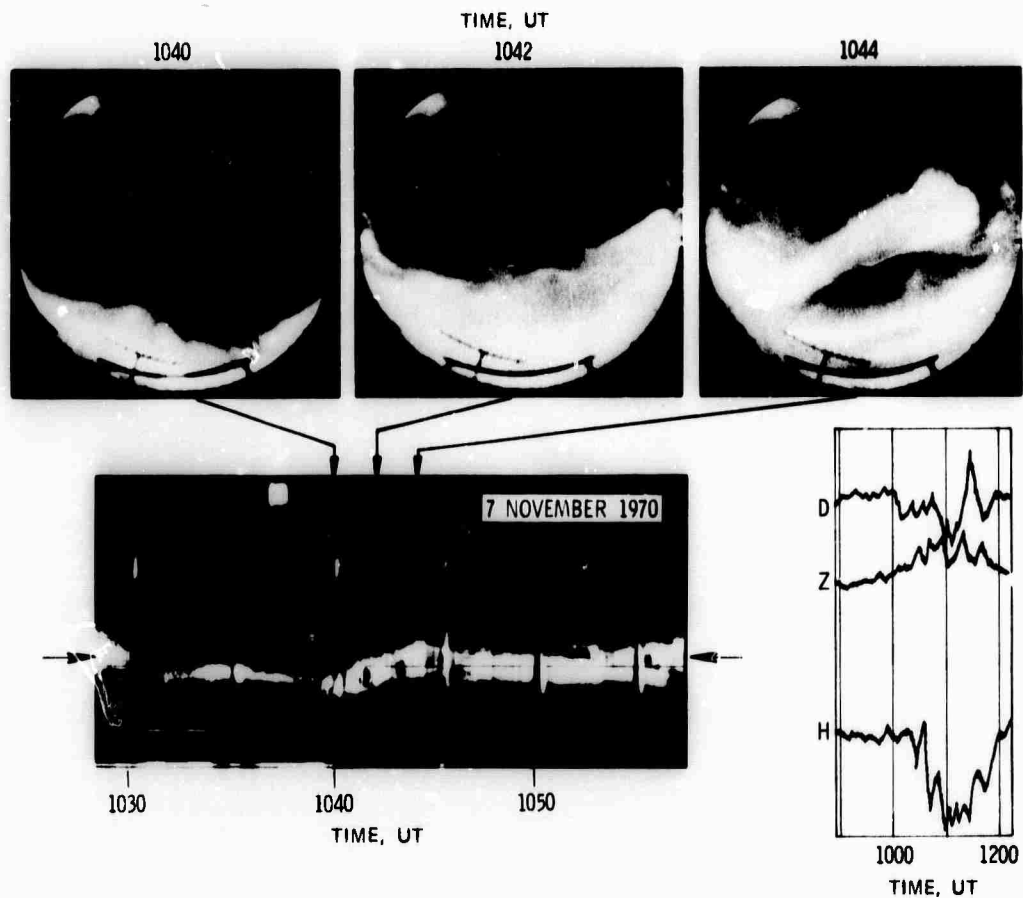


FIGURE 12 THE ALL-SKY-CAMERA, MAGNETOGRAM, AND NEWLY DISCOVERED AURORAL-RADAR SIGNATURES OF A SUBSTORM POLEWARD EXPANSION THAT REACHED COLLEGE, ALASKA, AT 1042 ON 7 NOVEMBER 1970

It is noteworthy that not a single one of the seven cases of radar aurora moving rapidly from the south to the north over College was followed within a few minutes by reception of an AIW at College, while southward motions often (although by no means always, as discussed in Section III-C) are followed by AIW's.

This is consistent with Wilson's theory (private communication) of AIW generation by momentum transfer to the neutral gas from ions undergoing a Pedersen drift in the auroral E layer. According to this view, the southward-moving forms have a velocity component parallel to the Pedersen drift and produce an AIW shock front, while the northward-moving forms have a velocity component antiparallel to the Pedersen drift and do not produce a detectable AIW shock even if moving supersonically.

**BLANK PAGE**

## IV HF-DOPPLER STUDIES OF F-LAYER PHENOMENA

### A. The CW-Doppler Technique

The results obtained with a high-latitude HF-Doppler array over a six-week observing period during October and November 1970 will be described in this section. The experiment, designed primarily to establish the feasibility of detecting and measuring the speed and travel direction of TID's at high latitudes, was successful. Two excellent TID events were detected. These had many cycles of regular fluctuations that persisted for at least four hours. Many other TID's were observed, some of which appeared to be non-auroral related since they apparently did not arrive from the polar region.

In addition, two unusual events were discovered that are believed to be unique to the high-latitude location of the array. These results will be discussed in detail in Section IV-C. Prior to this, the CW-Doppler technique, the nature of signatures expected from a TID, and the Alaskan array will be described. The section is concluded with a discussion of the relationship between TID's and AlW's.

#### 1. Doppler Signature Produced by Ionospheric Disturbances

When a very stable HF radio signal is transmitted through a time-varying medium, the frequency of the received signal will in general be different from the transmitted one. For ionospheric propagation, the frequency perturbations of the received signal are usually a few hertz, or less, with quasi-periods ranging from about 20 seconds to more than one hour. These perturbations are directly related to changes in the phase path of the probing radio signal as given by Eq. (1) in Table 4, or to changes in the electron density ( $N$ ) along the radio path [Eq. (2)]. For the special case of a small change in the height of a layer having a fixed shape (change in reflection height), the Doppler shift,  $\Delta f$ , is

Table 4  
SUMMARY OF SOME USEFUL FORMULAE

Equation Number	Equation and Comment	Assumptions	Reference	Definition of Symbols
(1)	$\Delta f = - \frac{f}{c} \frac{dp}{dt}$ Basic Equation	Time and Space Variation of ionosphere slow compared to $f$ (SVI)	Davies, et al., 1962	$t$ = Time $f$ = Transmitter frequency $P = \int \mu \cos \alpha \, ds$ phase path $\alpha$ = Angle between ray path and wave normal $s$ = Ray-path length, measured from transmitter to point of interest $c$ = Speed of light, $3 \times 10^8$ m/s $N$ = Electron number density $\mu$ = Refractive index given by the Appleton-Hartree equation $V$ = Velocity of reflecting surface. Subscripts $v$ and $h$ represent vertical and horizontal velocities, respectively $\Delta H$ = Fluctuation in the horizontal component of geomagnetic field $h$ = Height of reflecting surface
(2)	$\Delta f \propto \frac{1}{cf} \int \frac{1}{\mu} \frac{\partial N}{\partial t} \, ds$	SVI Concentric ionosphere (CI) No Magnetic Field (NF) No Collisions (NC)	Agy, Baker, Jones, 1965 Lewis, 1967	
(3)	$\Delta f = - \frac{2fv}{c} \propto f$ Specular Reflection	SVI, NF Stationary Transmitter and Receiver (STR) Vertical-Incidence Propagation (VI)		
(4)	$\Delta f \propto f^{-1}$ Nondeviative layer ( $\mu \approx 1$ )	SVI, NF, STR, NF, NC, CI	Davies and Baker 1966	
(5)	$\Delta f \propto \Delta H$ Hall Drift Model	Current flowing in the E-region produces fluctuating magnetic field at surface of Earth	Duffus and Boyd, 1968	
(6)	$\Delta f \propto \frac{d}{dt} \Delta H$ Sudden Commencement Model		Duffus and Boyd, 1968	



Table 4 (concluded)

Equation Number	Equation and Comment	Assumptions	Reference	Definition of Symbols
(7)	$\Delta f \propto \Delta H f^{-1/2}$ Alfvén Wave Model		Duffus and Boyd, 1968	See preceding page
(8)	$A^2 \propto 1 - \frac{h}{2V_h} \frac{d^2 p}{dt^2}$ $= 1 + \frac{h}{2V_h} \frac{c}{f} \frac{d}{dt} \Delta f$		Whitehead 1956	

proportional to the transmitted frequency and is given by Eq. (3). This case represents the specular reflector model and is particularly useful in interpreting TID's, as will be shown later.

A change in the medium below the reflection height produces a Doppler shift that is inversely proportional to the signal frequency, as shown by Eq. (4). In general, contributions to  $\Delta f$  may occur all along the radio path, but in practice, due to the  $1/\mu$  weighting factor in Eq. (2), the region near reflection seems to be the most effective for producing the fluctuations associated with TID's. Furthermore, if one takes the generally accepted view that TID's are a manifestation of internal gravity waves,\* the importance of this region is reinforced, for the following reasons:

- (1) The amplitude of internal gravity waves increases with height. Hence, for a given probing frequency the perturbation amplitude (along the radio path) will be greatest at the reflection height.
- (2) The value of  $\partial N/\partial t$  due to internal gravity waves alternates in sign, hence the integration of Eq. (2) along the radio path tends to cancel (Georges, 1968; Baker and Cohen 1971).

Multi-frequency Doppler sounding can be used to decide whether Eq. (3) or Eq. (4) applies to a particular event. While data of this type were not available for the present experiment, the results of past mid-latitude measurements have generally confirmed that Eq. (3) applied to the events of interest here (Georges, 1967, 1968; Chang, 1969). An important case in which contributions well below the reflection height

---

\* Although other mechanisms like ducted acoustic-gravity-wave modes have been suggested (Wickersham, 1964, 1965, 1966), the evidence that medium-scale TID's are caused by internal gravity waves is substantial (Georges, 1968; Davies and Jones, 1971). Furthermore the properties of TID's to be subsequently listed are consistent with the internal-gravity-wave interpretation of TID's.

dominate is solar-flare ionization due to X-rays (Donnelly, 1967). This type of event, however, will not be considered.

The disturbances depicted in Figure 13(b), called "switchbacks" (Georges, 1967), are believed to result from the same mechanism as those studied by Munro and his co-workers (Munro, 1950, 1953, 1958; Munro and Heisler, 1956a,b) using fixed and variable frequency techniques.

Figure 13 shows a simple model of an ionospheric disturbance along with the Doppler shift and path-length change that would occur. The cusp-type signature shown in Figure 13(c) is one that Munro would observe using a fixed-frequency pulse transmitter.

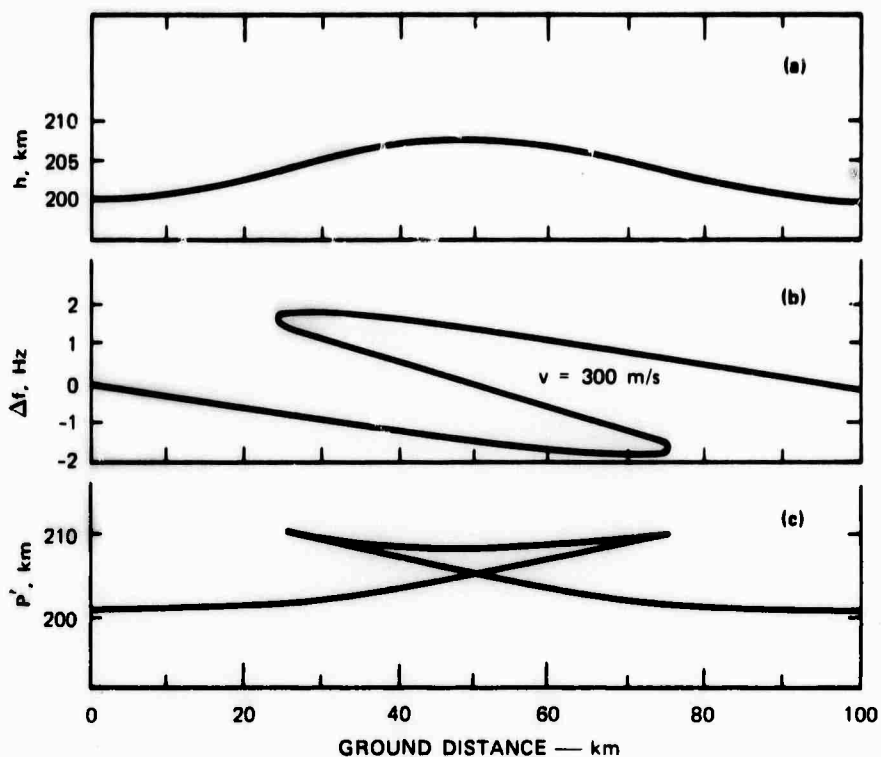


FIGURE 13 DOPPLER SHIFT AND PATH LENGTH FOR A SAMPLE DISTURBANCE (Georges, 1967)

Although "switchbacks" in Doppler records have been known for a number of years (Davies and Baker, 1966; Georges, 1967), they have not as yet been systematically studied. Some of their features that appear to have been fairly well established by past experiments are as follows:

- (1) Sequential time delays of radio signals reflected at different heights show a downward component of velocity (see Figure 30, Baker et al., 1968; and Figures 14 and 15 of this report).
- (2) The magnitude of Doppler fluctuations tends to be proportional to the probing frequency (see Figures 14 and 15).
- (3) When  $d\Delta f/dt$  is large, amplitude focusing is likely to occur [see Figure 16 and Eq. (8)].
- (4) Their periods generally lie between 14 and 30 minutes, with 20 minutes being most common.
- (5) Their features tend to change quite rapidly over distances greater than about 100 km (Georges, 1967).
- (6) They will show as much as 3 or 4 cycles of regular features.

The first three observations (1, 2, and 3 above) are consistent with the view that perturbation in the electron density ( $N$ ) is produced by internal gravity waves whose sources lie somewhere below the F layer. These waves have the property that for an upward flow of energy the wave front will be tilted forward (Hines, 1960). [This property of TID's has also been established through other experiments (Munro, 1953; Thome, 1964)]. The last three observations are related to the source of the gravity wave and/or the propagation medium. Their explanation rests on knowledge of the source and its location.

The principal features of a switchback (focusing, defocusing, shape of  $\Delta f$  vs. time, and occasional triple values of  $\Delta f$ ) are simply explained by a model that was originally proposed by Munro (1953). The model consists of the loci of radio reflection points in the height-vs.-

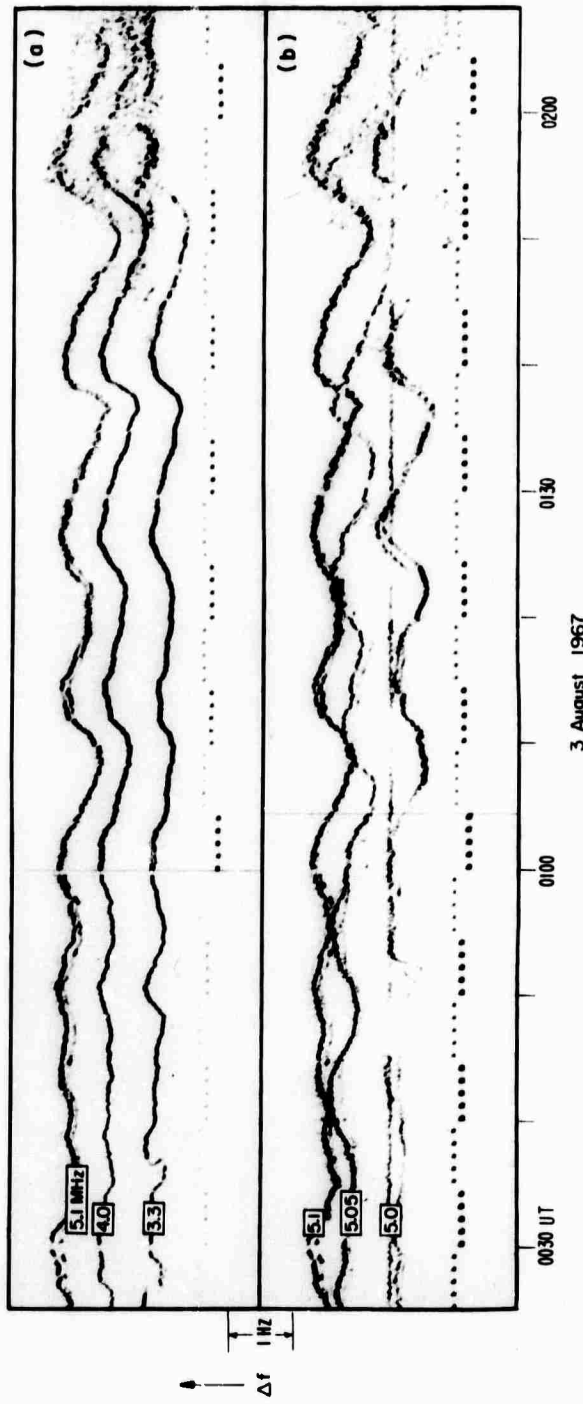


FIGURE 14 TRAVELING IONOSPHERIC DISTURBANCE WITH FIVE CYCLES OF REGULAR FLUCTUATIONS OBSERVED OVER BOULDER, COLORADO (Chang, 1969)

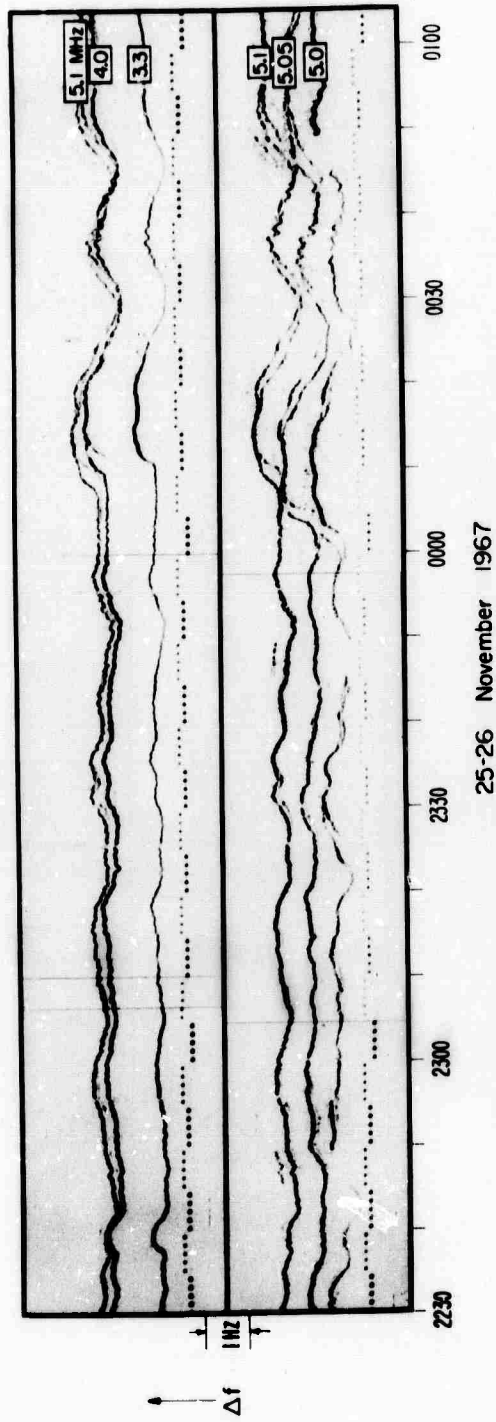


FIGURE 15 TRAVELING IONOSPHERIC DISTURBANCE OBSERVED OVER BOULDER, COLORADO. Note the progression of the disturbance from the highest frequency (5.1 MHz) to the lowest frequency (3.3 MHz).

30 APRIL 1966

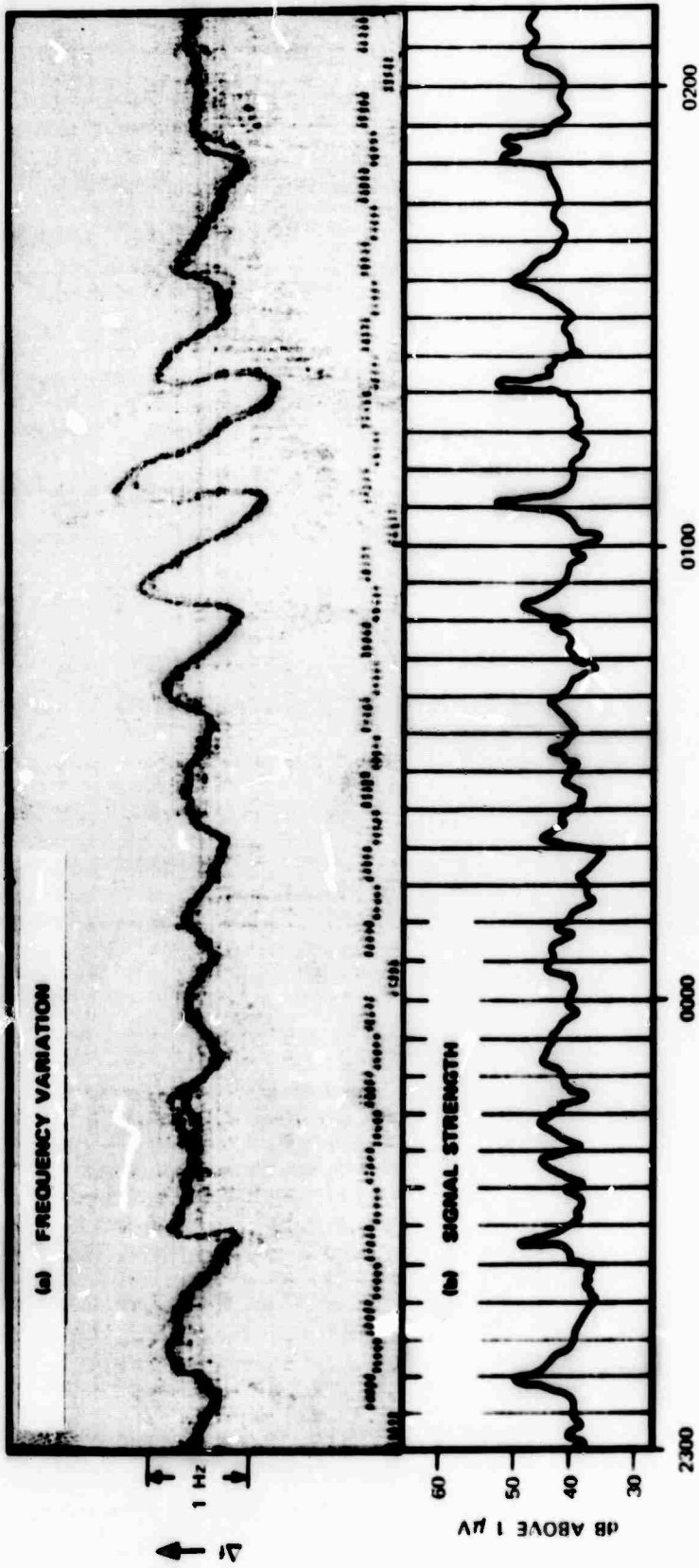


FIGURE 16 SIMULTANEOUS FREQUENCY AND SIGNAL-STRENGTH RECORDINGS OF A STEEP-INCIDENCE, 5.054-MHz RADIO SIGNAL ILLUSTRATING AMPLITUDE FOCUSING WHEN  $dJ/dt$  IS LARGE

time domain. To a first approximation, this surface coincides with the electron-density contour with plasma frequency of the necessary magnitude to reflect the incident radio wave.

An example of its utility in explaining the switchback signature is illustrated in Figure 17. Here the reflecting surface is fixed, and the observer moves from left to right as indicated by the arrows on ground plane A through D. (This is equivalent to a disturbance passing from right to left relative to a fixed observer.) The arrows above the reflecting surface indicate the movement of the ray's reflection point as the disturbance passes overhead. For example, Doppler shifts from a to b would be produced by traveling from a' to b' on ground plane D. The reflection point would move from a'' to b''.

Multiple echoes (switchbacks) occur whenever the reflection height of the radio ray is greater than the radius of the curved reflector.\* At these points (ground planes C and D) the Doppler trace may be triple-value since returns from three rays are possible. For ground planes A and B no switchback in  $\Delta f$  occurs because the reflection height of the ray is less than or equal to the reflection-surface radius of curvature.

Due to focusing and defocusing of the radio signal by the curved reflector, the amplitude of the received signal often shows a time variation. A good example of this can be seen in Figure 16. Here, in the lower frame, enhancements in the signal strength are clearly evident whenever  $\Delta f$  changes rapidly with time. Note, however, that the intensity of the Doppler trace in the upper frame remains fairly constant throughout. This is due to the AGC (automatic gain control) action of the Boulder receiver.

---

\* For a given ionosphere the radius of curvature of the specular reflection is related to the amplitude of the perturbing internal gravity wave. Hence, the presence of a switchback on the Doppler record indicates a larger disturbance than a quasi-sinusoidal fluctuation.



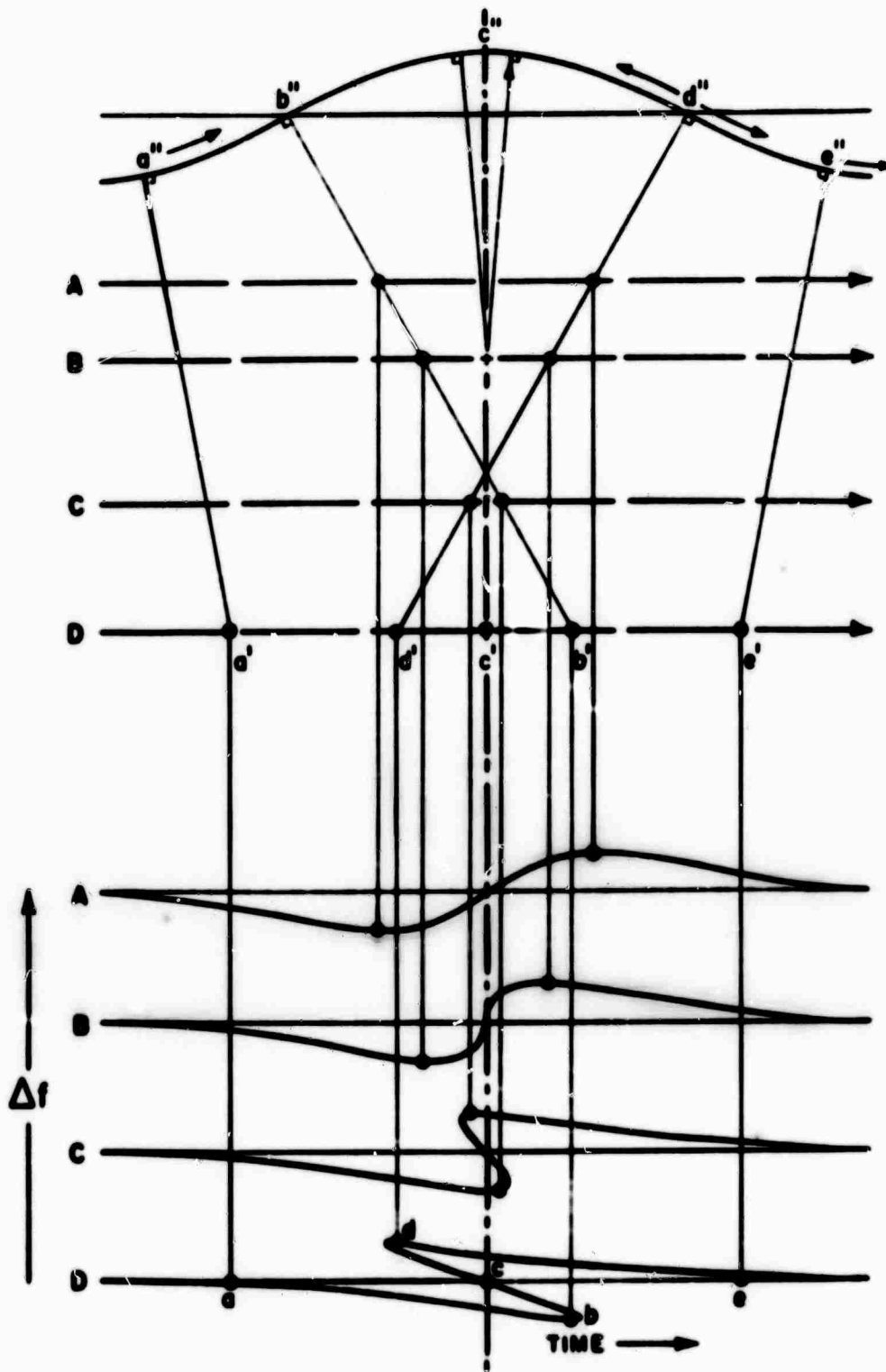


FIGURE 17 ILLUSTRATION OF THE SPECULAR REFLECTOR AND THE NATURE OF DOPPLER SHIFTS OF RADIO SIGNALS REFLECTED FROM IT (Georges, 1967)

In the Alaskan system, the AGC was ineffective because of the 6-kHz bandwidth of the receiver. Thus in all of the Alaskan data, the amplitude of the received signal is directly related to the intensity of the Doppler trace. Some examples of focusing and defocusing in the Alaskan experiment of the type predicted by Eq. (8) may be found in the early portion of Figures 25(a) and 28.

## 2. The Alaskan HF-Sounder Array

The Alaskan TID system consisted of a network of three very stable frequency transmitters located at various sites around the Kenai Peninsula in Alaska, as shown in Figure 18. The ionospherically reflected signal from each transmitter was received at Homer and recorded on magnetic tape for later processing at SRI. Each transmitter had an output of about 50 watts, but due to the delta antennas used, only about 25 watts were radiated. The transmission frequency at each site is as follows:

<u>Station</u>	<u>Frequency (MHz)</u>
Elmendorf	2.85
Seward	2.77
Wildwood	2.75

The CW (continuous wave) Doppler technique, which will be briefly described here, was developed by Watts and Davies (1960). Basically, the technique involves transmitting a radio signal with a frequency stable to about 1 part in  $10^8$ /day, and comparing the ionospherically reflected signal with another equally stable reference frequency. Figure 19 is a block diagram of the system used in the Alaskan network.

In general, the received signal will contain a time-varying component  $\Delta f(t)$ , which is proportional to the time rate of change of the phase path,  $P$ . This relationship is given by Eq. (1) in Table 4. The

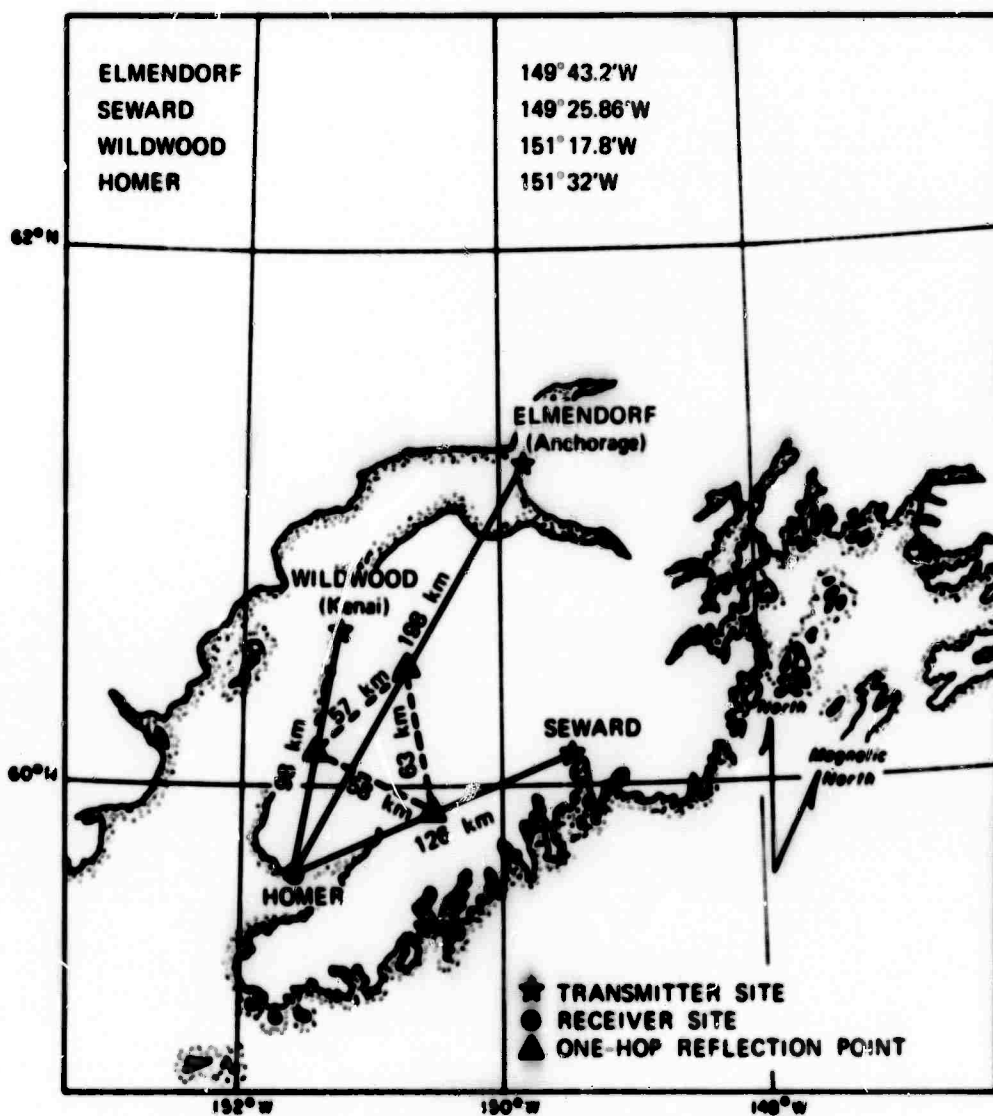


FIGURE 18 ALASKAN CW-DOPPLER ARRAY

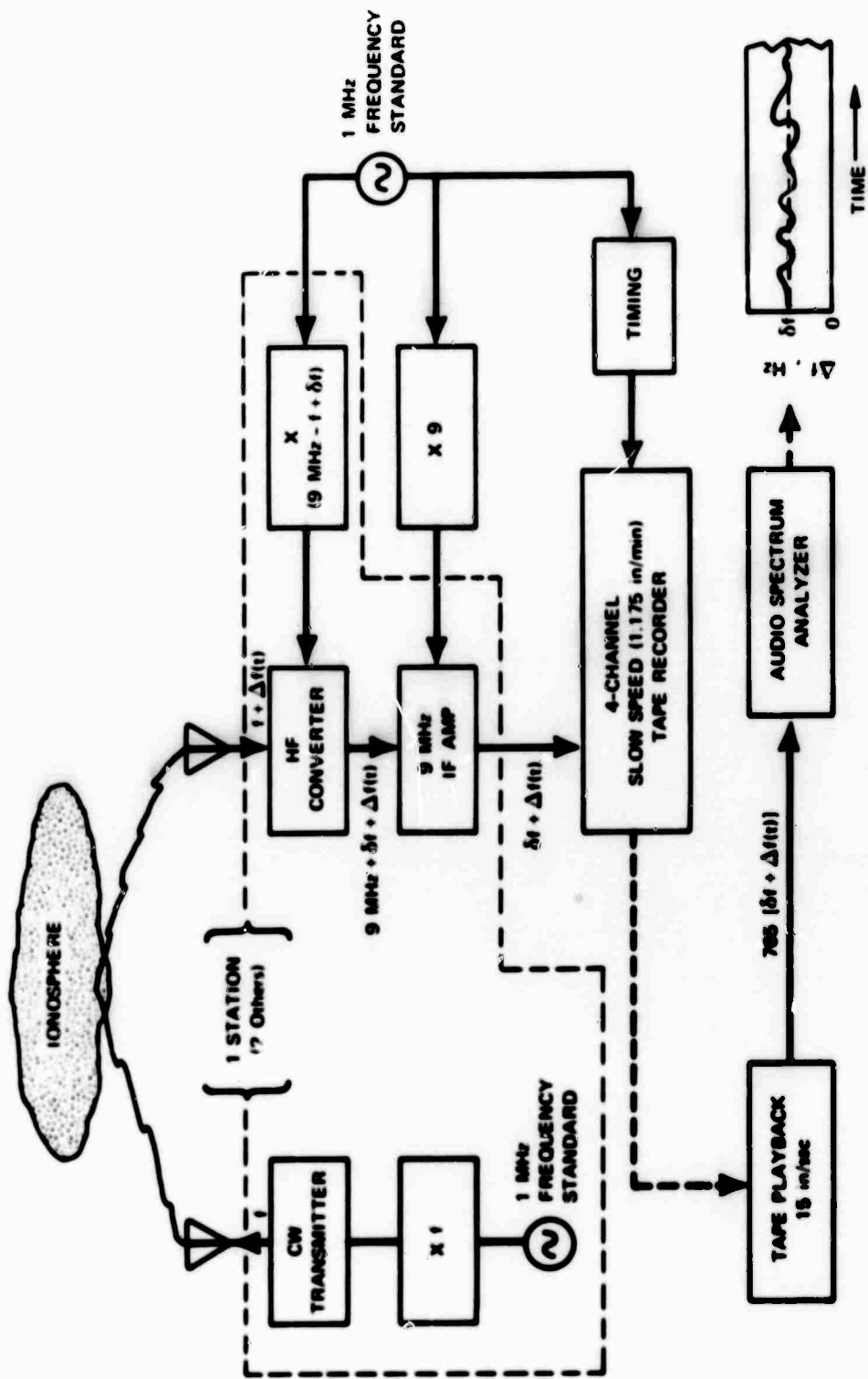


FIGURE 19 BLOCK DIAGRAM OF ALASKAN CW-DOPPLER NETWORK

incoming signal ( $f + \Delta f$ ) is added to a constant frequency (which is derived from a stable oscillator) such that the result is  $9 \text{ MHz} + \delta f + \Delta f(t)$ . This up-conversion is required in order to place the desired signal in the 6-kHz passband of the 9-MHz IF amplifier. The  $\delta f$  term is an offset of 2, 3, or 4 Hz used in order to separate the various channels on playback and in order to detect the sense of the Doppler shift,  $\Delta f$ , which is typically about 1 Hz. The low-frequency output of the IF amplifier is recorded on a slow-speed (1.175 inch/min) tape recorder using standard 1/4-inch audio tape. With this recording format, a single 1800-ft reel of tape lasts for about two weeks and contains each of the three received signals and timing on a separate track.

When the system was placed in operation it was found that, at times, because of extraneous signals, it was difficult to positively identify the transmitted signal. This was solved by installing at each site keyers set to turn the transmitters off for about a minute at pre-selected times. The details are given in Table 5.

Table 5

SUMMARY OF FORMAT USED FOR THE TRANSMITTER KEYERS

Station	Cycle Time (min)	Keying Time	Date Installed
Wildwood	60	On the hour	3 Nov.
Seward	70	-	4 Nov.
Elmendorf	60	10 min before the hour	6 Nov.

Processing of the Doppler tapes was done at SRI using a Raytheon Rayspan frequency analyzer. The particular model used consisted of 420 narrowband filters covering any 3-kHz band between 20 Hz and 20 kHz. Each filter was mechanically scanned 60 times a second and the output displayed

using a Granger Associates 9190 Recorder. The result is a frequency-vs.-time spectrum, as shown in Figure 20, where the blackening of the trace shows the relative power density in the spectrum. The output of the Granger recorder was particularly convenient because it was translucent and two or more traces could be overlaid and shifted with respect to each other to measure time shifts.

For timing, a time code was recorded on a separate channel simultaneously with the data. The code consists of a signal recorded for the first 20 seconds of each minute with the following format:

- (1) 1 Hz for the 2nd, 4th, ... 12th 5-minute period of each hour
- (2) 0.8 Hz for the 3rd, 5th, ... 11th 5-minute period of each hour
- (3) 0.65 Hz for the first 5 minutes of each hour of the day, except the 10th and 20th (UT) when no signal was recorded and the 00 (UT) hour
- (4) 0.5 Hz for the first 5 minutes of the 00 hour of each day.

Thus, the time is coded into 1-minute, 10-minute, 1-hour, and 24-hour marks, which can be easily distinguished by their tone on playback. The appearance of the time marks on the records can be seen in Figure 20. The equipment and format described above is essentially that used by Baker et al. (1968) and by Jones (1969).

Under normal processing of the Doppler tapes with the Rayspan analyzer, one hour of data is compressed into approximately 8 cm of display. Maximum scaling accuracy is about 12 seconds. When greater accuracy was needed, the data were processed with a Kay Electric Sonogram, where approximately 30 cm represents an hour. Here a scaling accuracy of 3 or 4 seconds is possible. Since accuracy was not limited by the time scale, all processing was done with the Rayspan analyzer. The one exception was the 13-14 November event, which, because of its quality, was

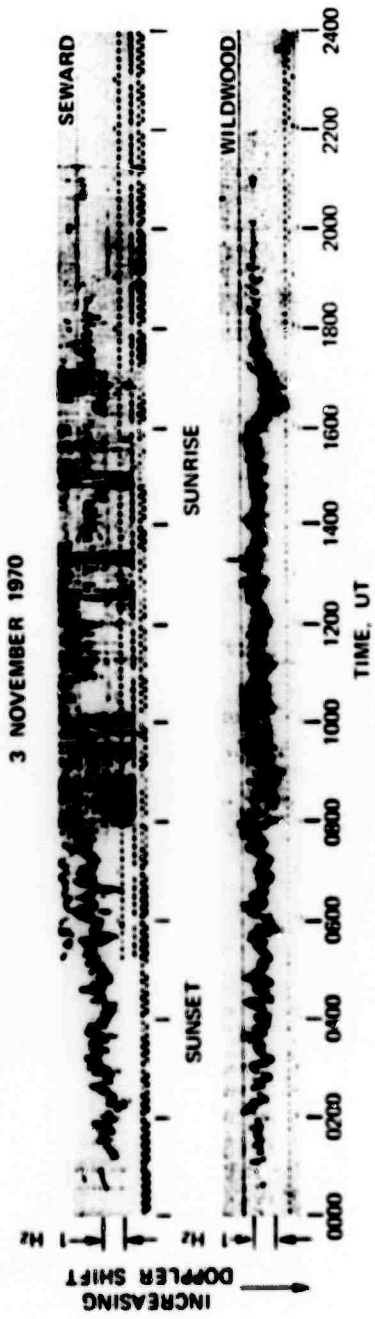


FIGURE 20 DOPPLER SPECTRUM OF SIGNALS FROM WILDWOOD AND SEWARD OVER A 24-HOUR PERIOD

using a Granger Associates 9190 Recorder. The result is a frequency-vs.-time spectrum, as shown in Figure 20, where the blackening of the trace shows the relative power density in the spectrum. The output of the Granger recorder was particularly convenient because it was translucent and two or more traces could be overlaid and shifted with respect to each other to measure time shifts.

For timing, a time code was recorded on a separate channel simultaneously with the data. The code consists of a signal recorded for the first 20 seconds of each minute with the following format:

- (1) 1 Hz for the 1st, 4th, ... 12th 5-minute period of each hour
- (2) 0.8 Hz for the 3rd, 5th, ... 11th 5-minute period of each hour
- (3) 0.65 Hz for the first 5 minutes of each hour of the day, except the 10th and 20th (UT) when no signal was recorded and the 00 (UT) hour
- (4) 0.5 Hz for the first 5 minutes of the 00 hour of each day.

Thus, the time is coded into 1-minute, 10-minute, 1-hour, and 24-hour marks, which can be easily distinguished by their tone on playback. The appearance of the time marks on the records can be seen in Figure 20. The equipment and format described above is essentially that used by Baker et al. (1968) and by Jones (1969).

Under normal processing of the Doppler tapes with the Rayspan analyzer, one hour of data is compressed into approximately 8 cm of display. Maximum scaling accuracy is about 12 seconds. When greater accuracy was needed, the data were processed with a Kay Electric Sonogram, where approximately 30 cm represents an hour. Here a scaling accuracy of 3 or 4 seconds is possible. Since accuracy was not limited by the time scale, all processing was done with the Rayspan analyzer. The one exception was the 13-14 November event, which, because of its quality, was



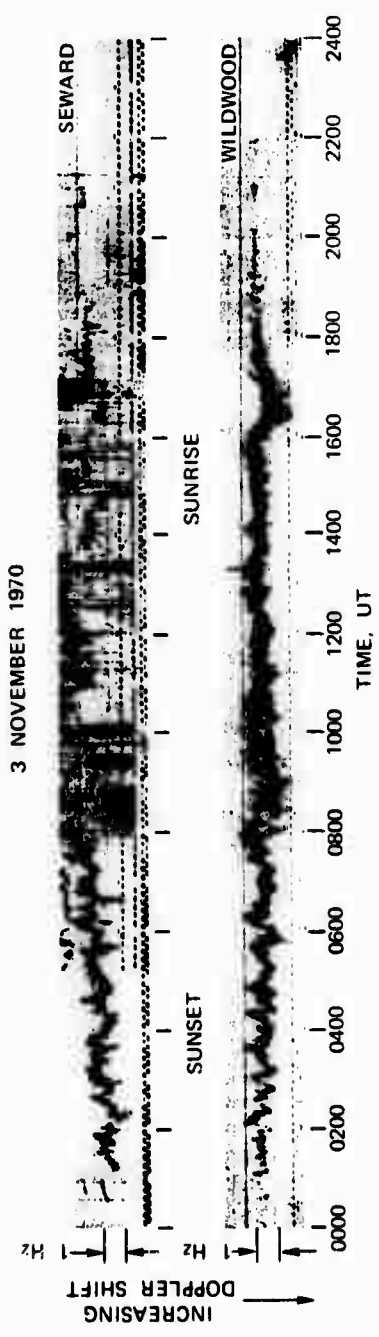


FIGURE 20 DOPPLER SPECTRUM OF SIGNALS FROM WILDWOOD AND SEWARD OVER A 24-HOUR PERIOD

also processed with the sonogram. In most cases the width of the Doppler trace and changes in the feature of a disturbance viewed over different radio paths (rather than the time scale) were the limiting factors.

Although there are a number of other techniques employed in studying traveling ionospheric disturbances, the CW-Doppler technique enjoys a number of important advantages over other methods. These are as follows:

- (1) It is a simple and inexpensive technique for continuous observation of the ionosphere. Perhaps no other technique is better suited for relatively unmanned operation on a patrol basis.
- (2) Because the data are stored in analog form, complex changes that produce spread and multi-value Doppler shifts are clearly evident after processing. These changes may be masked or lost by systems that produce only the Doppler spectra of the dominant frequency present, or that use analog-to-digital conversion.
- (3) Magnetoionic modes and multipath rays are automatically separated in the frequency domain because for a given disturbance the different modes and rays have different Doppler shifts.
- (4) Data reduction is simple and inexpensive, and subsequent interpretation is relatively straightforward.

The primary weaknesses of the CW-Doppler technique are that the range to the disturbance and the region of interaction between the disturbance and the radio wave are not known. This can be resolved somewhat by the use of multiple-frequency sounding and by ray tracing, but the latter requires knowledge of the electron-density profile along the ray path.

## B. Data Overview

A summary of the data obtained with the Alaskan CW-Doppler network is shown in Figure 21. The empty blocks represent periods when the received signal had a narrow spectrum. Periods when the spectrum was spread are indicated by the shaded blocks. The transmitters at Wildwood and Seward operated nearly continuously from 17 October to 27 November 1970. Their transmissions were received at least for a portion of each day with the exception of 23 and 31 October, and 1 November (see Figure 21).

The reason for the lack of data on 23 October seems to be related to the disturbed magnetic conditions. The sum of the Kp index on that day was 32, as shown by the right-hand column of numbers. The reason for the absence of data on the latter two days is not known, but the problem on 1 November could be attributed to a one- or two-hour power outage that occurred at Homer on 31 October at 2200 UT. Many hours are required for the frequency standard to restabilize after it cools. Propagation conditions and equipment seem to be normal prior to the power failure on 31 October and no explanation can be given for that data gap.

Signals from Elmendorf were received on 11 out of the 42 days of observations. These days are identified by parentheses in Figure 21. Transmitter failures were the cause of much of the data loss, but on one occasion (19 October to 25 October) an incorrect frequency setting at Homer was responsible.

Since two stations are generally sufficient to detect the presence of a TID, the detection mission of the network was not materially affected by loss of the third station during the periods indicated. With Doppler information from two stations, however, only a single velocity component and a general direction of a TID can be deduced.

The various symbols in Figure 21 indicate the occurrence of TID's, geomagnetic-related events, and unusual events on the Doppler records. In



FIGURE 21 SUMMARY OF CW-DOPPLER DATA AND OTHER PERTINENT INFORMATION. The column numbers on the right are the sum of the  $K_p$  indices for the respective day.

addition, the vertical bars show the occurrences of AIW's at College, Alaska (Wilson, private communication). The times of other events that may have some effect on the Doppler spectrum are shown on the upper and lower time axis. Sunset and sunrise at a height of 300 km are indicated by SS and SR, respectively. Periods when auroral absorption are at a minimum and maximum are denoted by MIN AA and MAX AA, respectively (Basler, 1963).

Representative records showing the Doppler spectrum (phase-path variations) over a 24-hour period are shown in Figures 20 and 22(a). During the day the Doppler spectrum is quite narrow, with small and rapid Doppler fluctuations compared to those that occur after about 0400 UT [see Figure 22(a)]. Since the Doppler method is capable of separating the magnetoionic modes and multipath rays, the narrow trace indicates that the signal probably arrived via the normal great-circle path between the transmitter and the receiver. The cause of the frequency fluctuations is interpreted to be movement of a fairly localized region of the ionosphere, probably near the radio reflection point.

After sunset, a smear appears about the main trace, apparently from irregularities that cause rays to arrive from off-great-circle paths. Most of the energy, however, continues to arrive over the great-circle path, as evidenced by the relatively narrow main trace. In Figure 20 the spectrum is completely smeared between 0800 and 1100 UT and no distinct trace is evident. The spread at this time indicates scatter from irregularities moving rapidly and in random directions relative to the transmission path. A somewhat distinct trace reappears after 1100, and after sunrise the Doppler trace becomes narrow again.

Sunrise causes an increase in ionospheric electrons due to photoionization. The net result is a decreasing radio phase path, which appears as an increase in Doppler shift. In Figure 20 the sunrise effect can be seen as a dip between 1600 and 1700 UT. In Figure 22(a) (note

5-6 NOVEMBER 1970

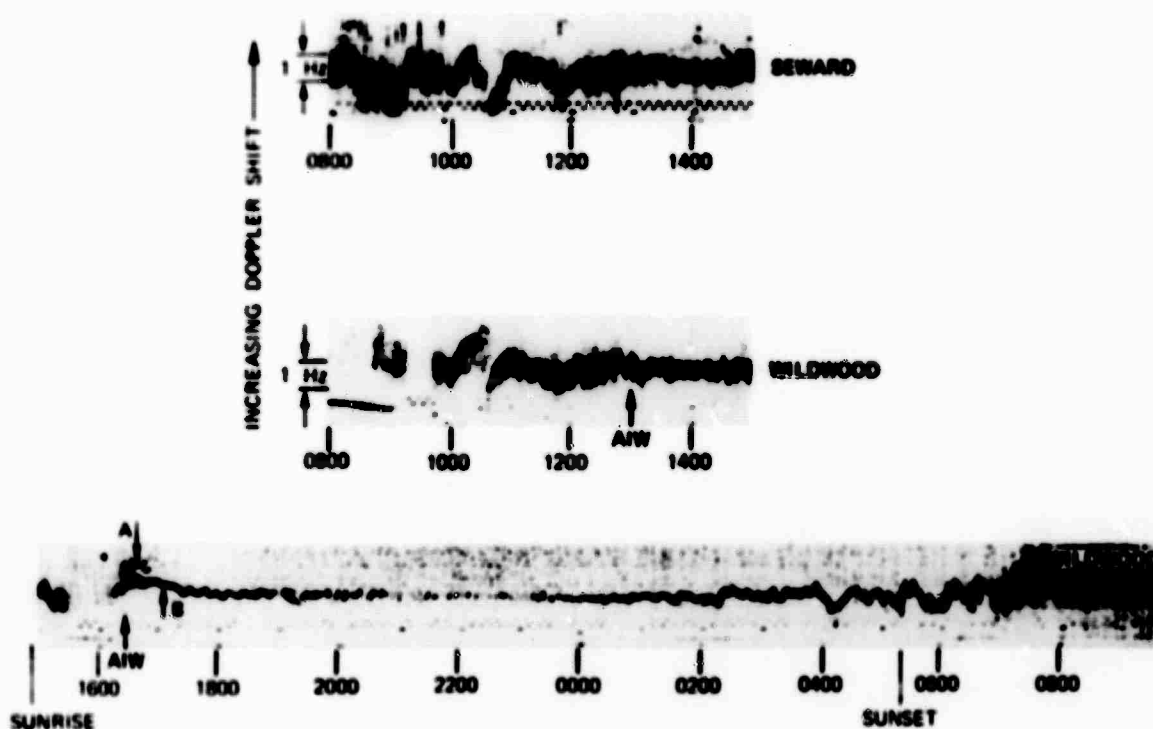


FIGURE 22(a) DOPPLER SPECTRUM OF SIGNALS FROM SEWARD AND WILDWOOD SHOWING DIURNAL VARIATION

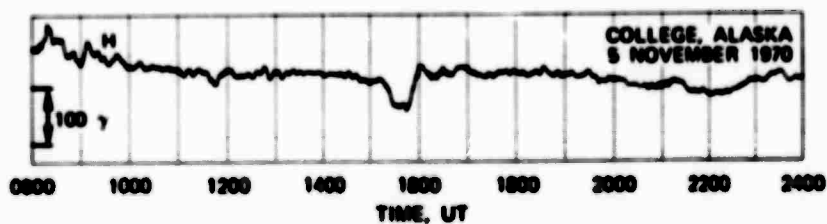


FIGURE 22(b) HORIZONTAL COMPONENT OF GEOMAGNETIC FIELD FOR 5 NOVEMBER 1970

the shift in Doppler polarity) the ray can be seen "coming in" after sunrise. [The possible effect of the magnetic bay occurring prior to 1600 UT--Figure 22(b)--will be discussed in Section IV-C.] The main ray (B) shows a decreasing Doppler shift with time while the Pedersen ray (A) has a Doppler shift increasing with time. This ray ultimately disappears due to signal loss through geometric spreading.

Around local noon (2200 UT) there is a distinctive absence of signals, probably due to normal D-region absorption. The fine structure present, however [see Figures 20 and 22(a)], suggests that auroral absorption,<sup>\*</sup> which peaks at this time, may also be a factor.

Concurrent transmission from Seward (Figure 20) shows a similar behavior, as discussed above, but between 0800 and 1700 UT interference has nearly masked its nature. The interference during this period was primarily due to propagated and local noise and not to the Homer radar, which normally operated from 0900 to 1500 UT. The interference usually began before the radar was energized and in this example extended two hours beyond the radar shutdown time. In addition, similar interference was present for the last four days of the experiment, when the radar was not energized at all. This shows conclusively that the primary source of interference was not the Homer radar.

For comparison, Doppler records from a mid-latitude path and one near the magnetic equator are shown in Figures 23 and 24. The sunrise effects in these figures are quite similar to the high-latitude examples. The mid-latitude Doppler record shows a change from short daytime periodicities (A) to longer nighttime periodicities (B), which are similar to the high-latitude results. The equatorial record, however,

---

\* Absorption due to bombardment of the upper atmosphere by primary auroral particles (Basler, 1963).

because of the long radio path, does not show much daytime fluctuation.

At night both the equatorial and the high-latitude examples show a spread spectrum in contrast with the mid-latitude record of Figure 23.

22-23 OCTOBER 1965

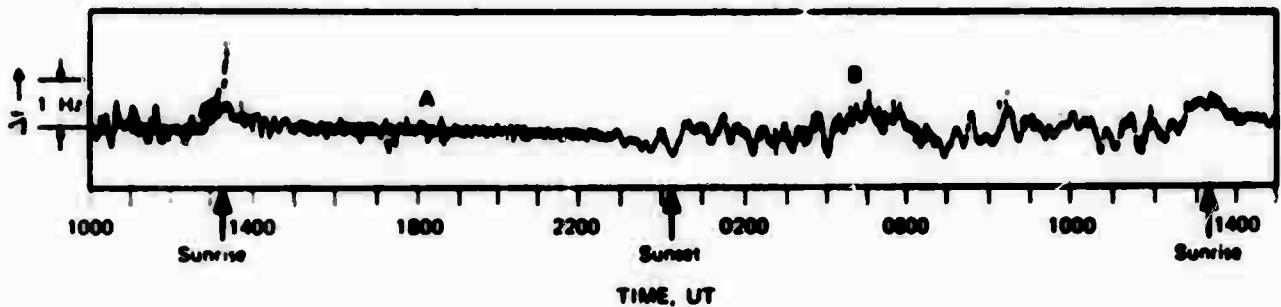


FIGURE 23 DIURNAL DOPPLER RECORD AT MID-LATITUDE, 3.3 MHz

With only six weeks of observations, little can be said regarding the morphology of TID's. The data, however, show that there is a tendency for them to occur shortly after sunrise and near sunset. Undoubtedly these results are prejudiced by observational selection. It can be said, nevertheless, that the present experiment has revealed a wealth of different events. These will be discussed in greater detail in the following section.

#### C. The High-Latitude Observations--Discussion of Results

Despite the prospects that TID's are generated in the polar regions, there have been few systematic measurements of TID's at high latitude. Jones (1970) describes a spaced-receiver CW-Doppler network that was established in the Antarctic to study the effects of traveling ionospheric disturbances on the ionosphere there. The observations revealed Doppler traces that were generally spread throughout the day with no correlation over two or more radio paths. Because of this it was not possible to identify any TID's.



DOPPLER SPECTRUM RECORDS  
 MONROVIA, LIBERIA TO ACCRA, GHANA  
 10.1018 MHz

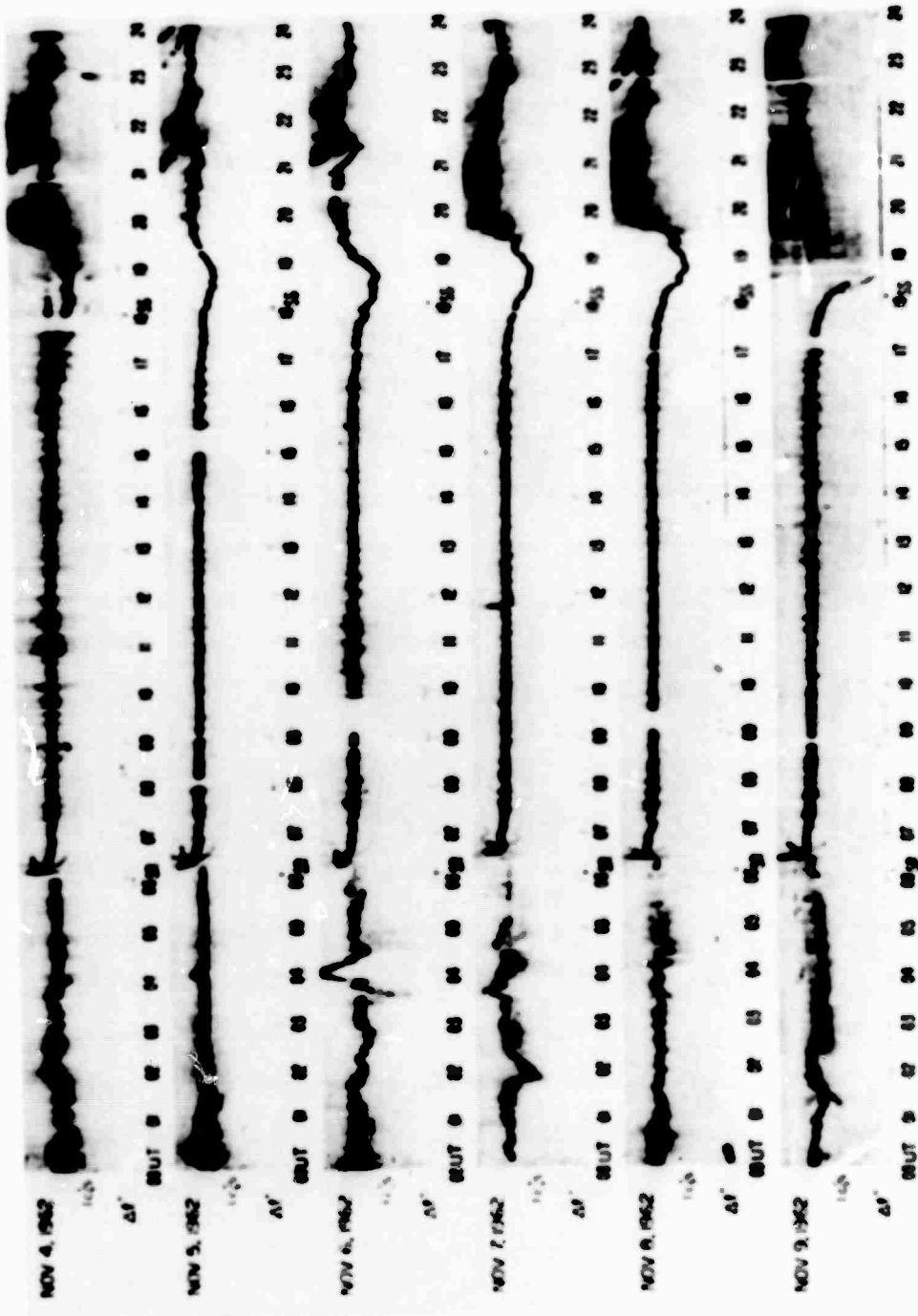


FIGURE 24 DOPPLER SPECTRUM FOR A 1180 km PATH NEAR THE MAGNETIC EQUATOR (L<sub>1180</sub>, 1964)

The Alaskan Doppler network, on the other hand, has clearly demonstrated the feasibility of TID detection at the Homer site. Long trains of TID's were observed on at least two occasions. Their sequential time delays and their times of occurrence are consistent with the hypothesis that their sources lie near the midnight sector of the auroral oval. These events indicate that if sufficient observations were made, it would be possible to test the hypothesis that the sources of TID's lie within the auroral oval. Furthermore, if the sources lie near the midnight sector of the oval, it should be possible to track the source region as it rotates around the geomagnetic pole.

Several types of events will be considered in detail in this section. These include TID's, Doppler signatures that correlate with geomagnetic fluctuations, and a number of newly discovered Doppler signatures that appear to be unique to the high-latitude location of the Alaskan network.

#### 1. Traveling Ionospheric Disturbances

Inspection of the Doppler records obtained over the six-week observing period has revealed times when the spectrum of the signal from each transmitter shows distinctive fluctuations, with amplitudes of about 1 Hz. These changes generally appear to be random, but there are periods when they show a high degree of visual correlation in addition to time displacements between pairs of traces. The time shift indicates a horizontal motion of a perturbing mechanism across the radio paths. These disturbances are generally referred to as traveling ionospheric disturbances (TID's) and are believed to be a manifestation of internal gravity waves (Hines, 1960).

Georges (1967, 1968) has distinguished between two classes of TID's, which he categorizes as "medium scale" and "very large." Generally he found that medium-scale TID's have speeds of less than 300 m/s with

periods between 10 and 40 minutes. They occur mostly during the day in trains of a few cycles (3 or 4 cycles) and show no correlation with any known geophysical event.

Very large TID's, on the other hand, travel at speeds in excess of 300 m/s, have periods between 30 minutes and an hour or more, and generally come from the north (in the northern hemisphere). They usually have one to three "cycles" of regular variations and seem to be closely related to high magnetic activity. This classification of TID's will also be adopted in this report.

The criteria used in the selection of TID's were (1) the existence of a definite feature at two or more stations with a measurable time displacement between traces, and/or (2) switchback signature at two or more stations. Thirteen events that satisfy one or both of these conditions are listed in Table 6.\* Of these events, four are classified as very large and the remainder as medium-scale.

a. Medium-Scale TID's

An exceptionally good example of a medium-scale TID is shown in Figure 25(a). This disturbance consists of a train of at least 12 cycles of regular fluctuations with periods in the range 14 to 20 minutes. Between 0100 and 0300 UT, regular fluctuations of about 1 Hz can be clearly seen on the Elmendorf and the Seward traces. Even on the time scale used, the switchback signatures with occasional triple values of  $\Delta f$  are quite evident.

Throughout the record, the trace often shows a darkening when  $d\Delta f/dt$  is large. This is probably caused by focusing as predicted

---

\* Although a cross-correlation technique undoubtedly would have revealed more events, only those with high visual correlation were considered.

**Table 6**  
**TID'S OBSERVED WITH THE ALASKAN CW-DOPPLER NETWORK**

Date	Time (UT)	Type*	Sequence <sup>†</sup>	Δt (min)	Number of Cycles	"Period" (min)
17 Oct	0625	VL	E, S W	1.0, 1.4	1/2	22
21 Oct	0500	MS	S, W	6.0	3	20
22 Oct	0630	MS	S, W	9.0	3	20
24 Oct	1800	MS	?			
5 Nov	0200	MS	W, S	6.0	> 12	13 - 20
8 Nov	1800	MS	W, E	1.0	2	15
9 Nov	0600	VL	E, S, W	2.0, 1.4		
13 Nov	0500	MS	E, S	5.0	2	25
*13-14 Nov	0200	MS	E, W, S	2.7, 4.3	> 12	15 - 20
*17 Nov	1915	VL		0 <sup>+</sup>	1/2	70
18 Nov	0300	MS	W, S	4.2	3	22
18 Nov	1930	VL	S, W	3.4	1/2	100
*20 Nov	2100	MS	W, S	7.5	8	10

★ MS - Medium-scale  
 VL - Very large

† E - Elmendorf  
 S - Seward  
 W - Wildwood

\* This event was classified as a TID because of its resemblance to the event of 18 November.

13-14 NOVEMBER 1970

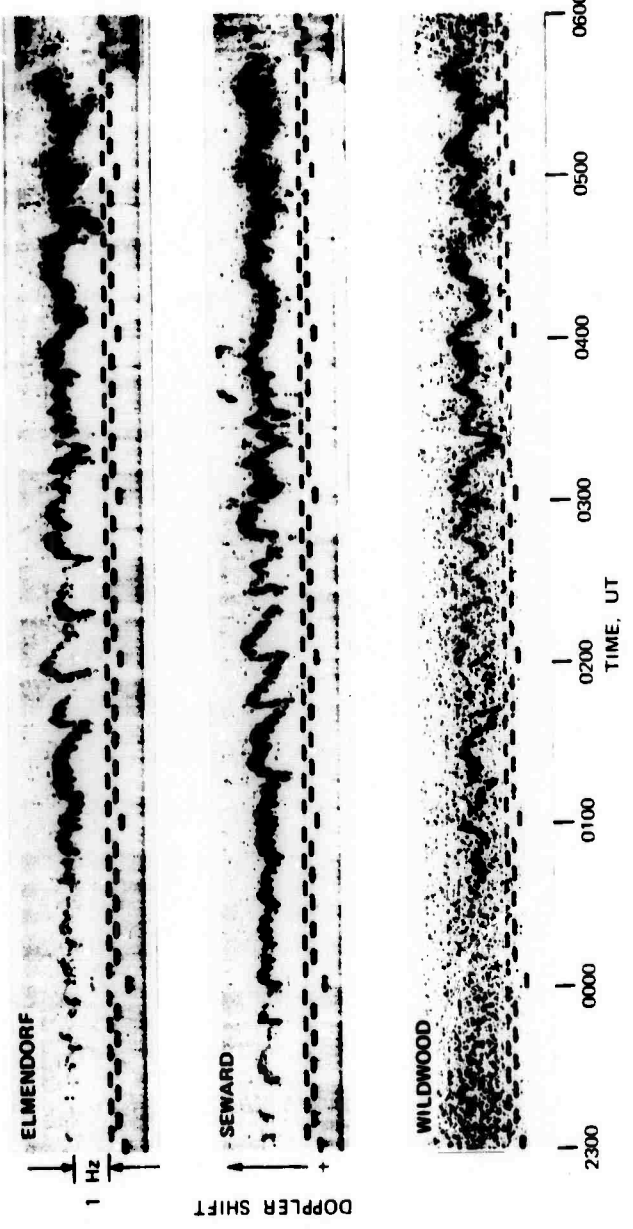


FIGURE 25(a) LONG-DURATION MEDIUM-SCALE TID OBSERVED OVER THE HOMER CW-DOPPLER NETWORK

by Eq. (8). The signal-to-noise ratio is low on the Wildwood channel over the above interval, but there are sufficient details visible for this trace to be compared with the Elmendorf and Seward signals.

Prior to 0100 the switchback signatures are less distinct but they can be seen to occur as early as 2300 UT. Before this time the signals were weak, but there are indications that the event may have started an hour or two earlier than shown by Figure 25(a). Even considering only the interval shown, the long duration of the event (more than four hours) and the many cycles of regular features are unique to the high-latitude station; a similar long duration event has not been observed at mid-latitude.

Figure 25(b) shows a tracing of the H component of the earth's magnetic field around the time of the 13-14 November TID described above. A magnetic bay can be seen near 1330 UT, too early to be associated with the TID that occurred over the Alaskan array between 2300 and 0300 UT. After about 1900 UT, magnetic activity was quite low. Thus, the above TID appears to be unrelated to local magnetic activity as measured by the College magnetogram. However, since TID's are known to travel global distances, the generation of this TID may still be related to magnetic activity at the source region.

Figure 26 shows a tracing of a portion of the event with the time axis of the Seward (S) and Wildwood (W) channels shifted with respect to the Elmendorf channel (E). The traces were displaced to maximize visual correlation between the various features. The sequential time delays between the three traces indicate that the disturbance arrived from an azimuth of  $350^{\circ}$ , traveling with a horizontal trace speed of 160 m/s.

Slightly different values were obtained using data playback from the sonograph. The arrival direction was  $345^{\circ}$ , and the horizontal trace speed was 150 m/s. Since the sonograph provides better time

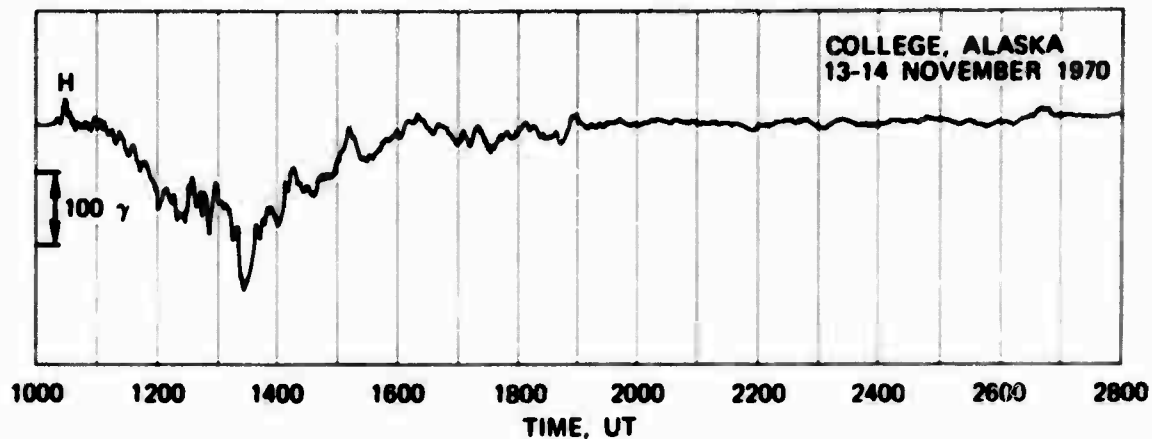


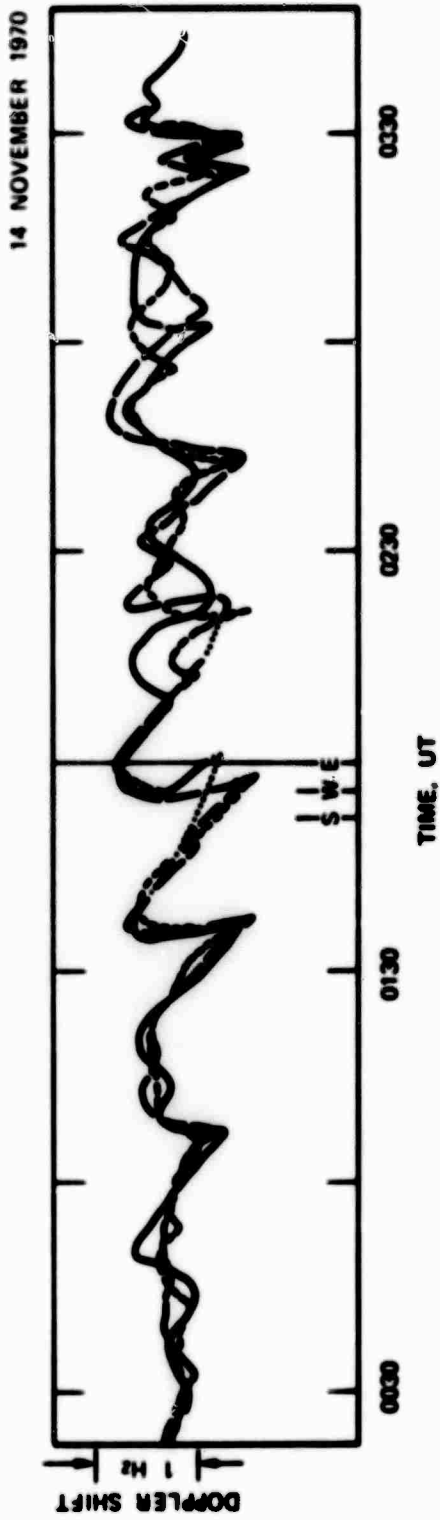
FIGURE 25(b) HORIZONTAL COMPONENT OF THE GEOMAGNETIC FIELD FOR 13-14 NOVEMBER 1970

resolution than the Rayspan analyzer (see Section IV-A), the values from the latter instrument have been used in the construction of Figure 27.

This illustration shows the great-circle path that passes through the Alaskan network with an azimuth of  $345^{\circ}$ . Increments of 1000 km are indicated by tick marks along the direction of arrival. The travel times at Homer for various ranges are tabulated in the accompanying table. These times assume that the disturbance traveled with constant horizontal velocity of 150 m/s.

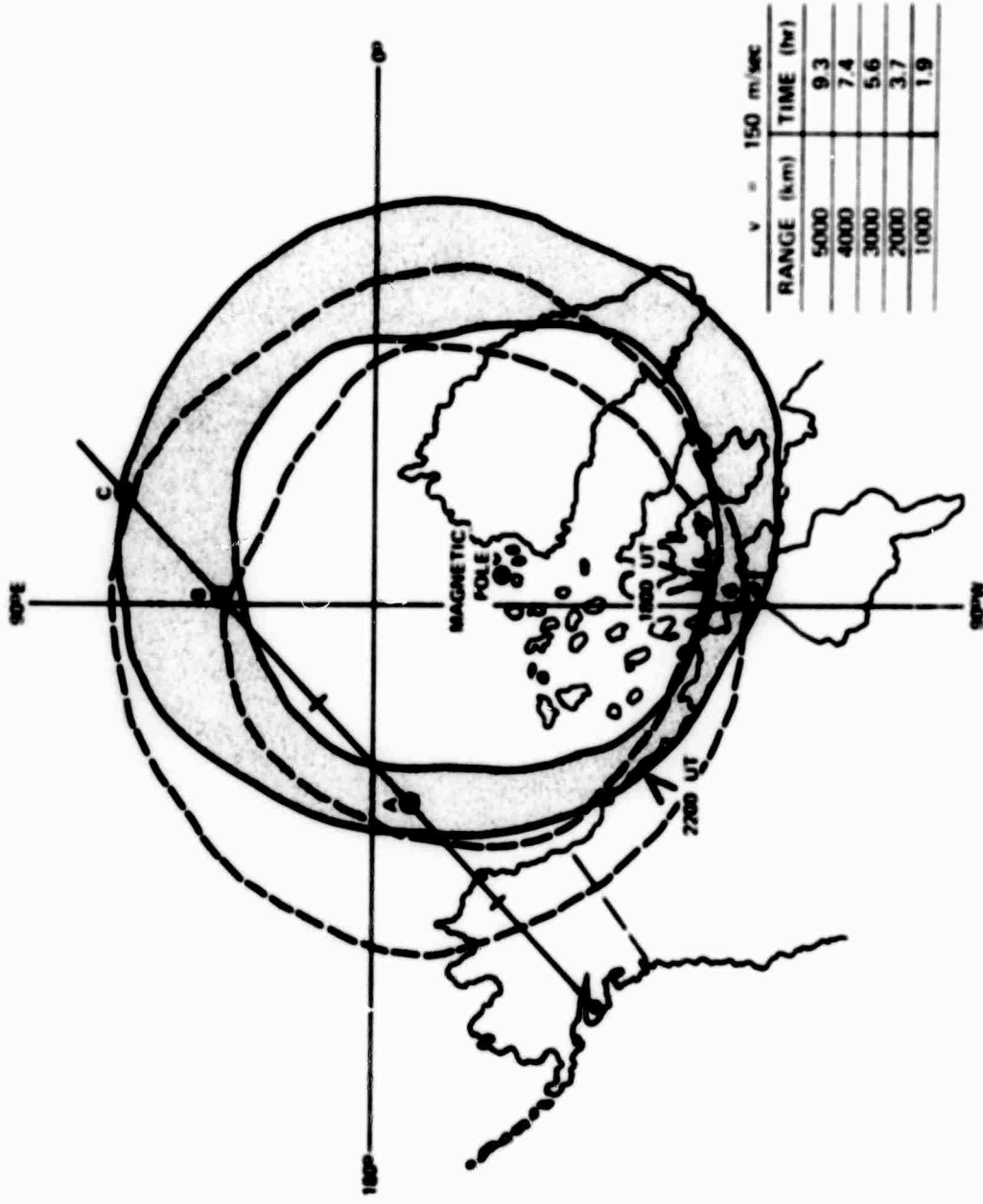
The locations of the auroral oval at 1800 and 2200 UT are also shown in the figure. If the source of the 13-14 November TID were near "A" (on the 2200 UT oval), the travel time to the Homer network would be about 4 hours and the disturbance would be detected near 0200, in agreement with Figure 26. Similarly, if the source were near the midnight sector of the auroral oval ("B" and "C" on the 1800 oval), then the travel time would be about 7 to 9 hours and the disturbance again would arrive at Homer between 0100 to 0300 UT.

Although one might expect other positions of the auroral oval to yield arrival times that are consistent with the observation, the



**FIGURE 26** TRACING OF A PORTION OF THE 13-14 NOVEMBER TID SHOWING THE TIME SHIFTS OF THE DISTURBANCE ON THE SEWARD (S) AND WILDWOOD (W) PATHS RELATIVE TO THE ELMENDORF (E) PATH





**FIGURE 27** POLAR VIEW SHOWING THE DIRECTION OF ARRIVAL OF THE 13-14 NOVEMBER TID RELATIVE TO THE POSITION OF THE AURORAL OVAL AT 1800 AND 2200 UT. The travel times for a disturbance moving with a constant velocity of 150 m/s are tabulated at the lower right for various travel distances to Homer.

variables (direction of arrival, velocity, and onset time of the TID) prove to be fairly restrictive. The direction of arrival does not intersect the 0200 to 0600 UT positions of the auroral oval. At other times, when it does intersect the oval, possible source regions common to the direction of arrival and the oval do not lead to the observed arrival time.

Another example of a long-duration, medium-scale TID is shown in Figure 28. This event is similar to the event shown in Figure 28. This event is similar to the event shown in Figure 25(a) in its persistence and its many cycles of regular features. Unfortunately, the Elmendorf transmitter was not in operation, so the direction of arrival and the velocity of this event can only be estimated. The occurrence of features on the Wildwood channel 6 minutes before they occur on the Seward path is consistent with a source in the same general location as the 13-14 November event.

With such a small data base it is only possible to tentatively relate the source of TID's with the auroral oval. The proximity of the Homer site to the oval, however, means that if the sources of TID's are located on the oval, then TID direction of arrival should on the average lie within a cone with azimuths of  $90^{\circ}$  and  $310^{\circ}$ . Furthermore, if the sources lie near the midnight sector of the oval then the directions of arrival should tend to be an ordered function of time. Thus, a plot of TID azimuth of arrival vs. observation time should produce a plot very much like that for AIW's (Wilson, 1969a).

One of the puzzling characteristics of medium-scale TID's found in past studies is that they seem to travel global distances with little attenuation, yet individual "wave cycles" are not coherent over distances greater than about 100 km (Georges, 1967).

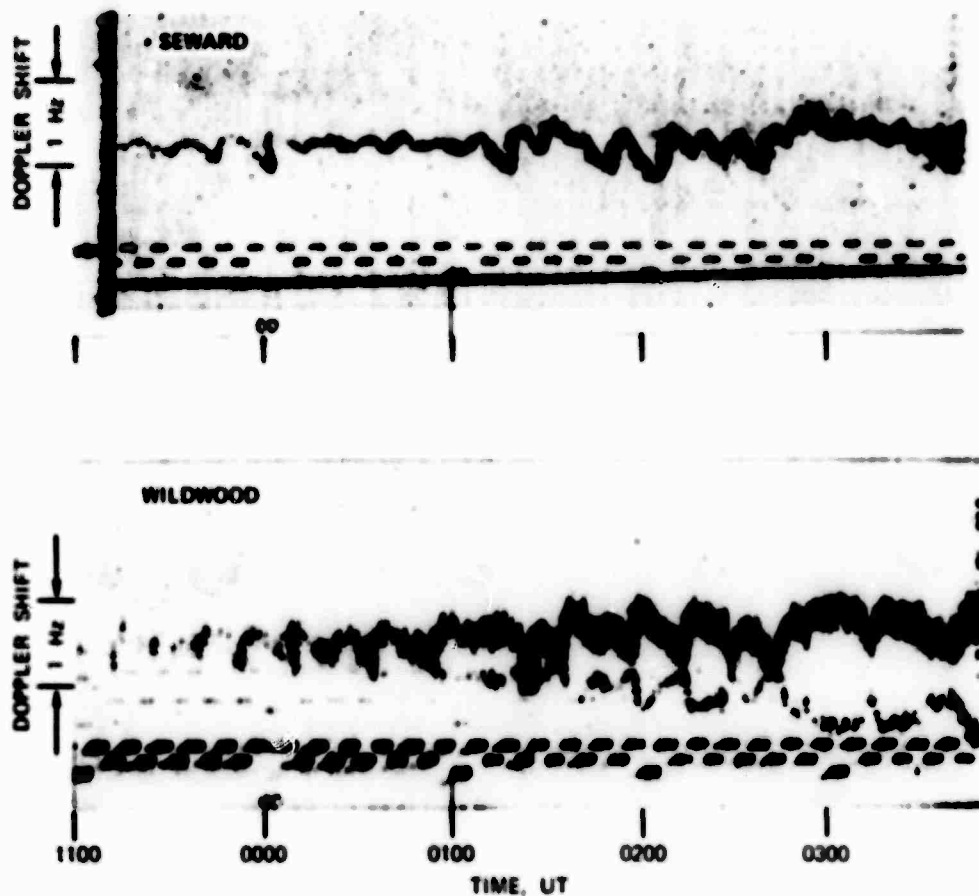
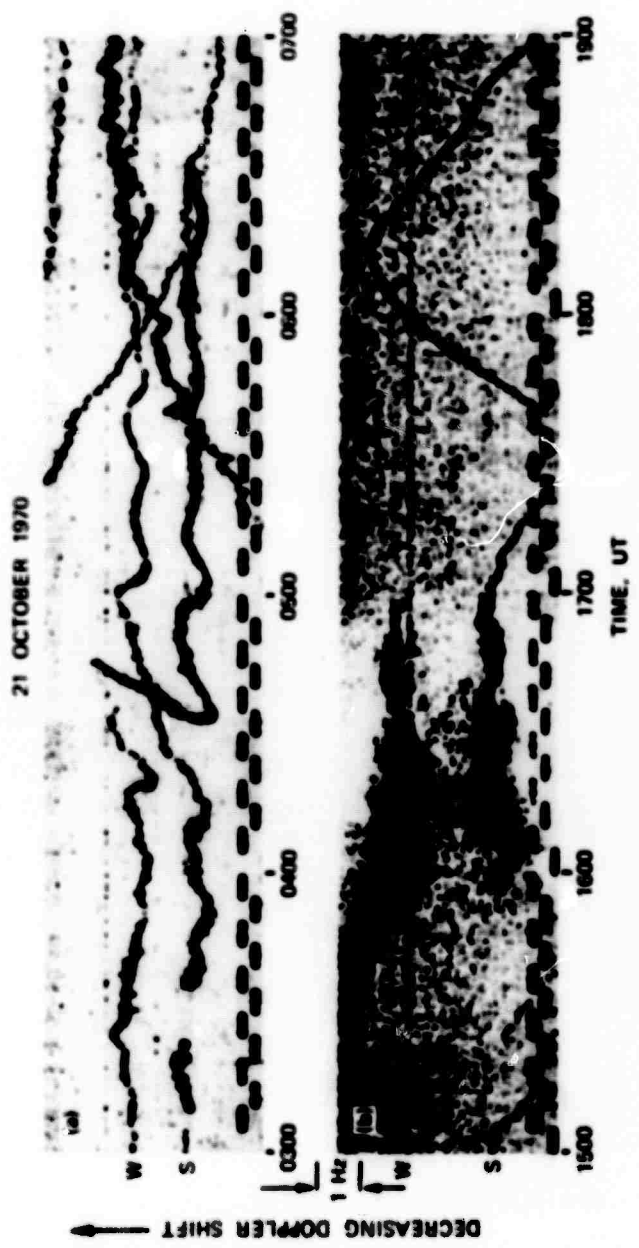


FIGURE 28 A LONG-DURATION MEDIUM-SCALE TID OBSERVED OVER THE SEWARD AND WILDWOOD PATHS

Figures 29(a), 30, and 31 show examples of three medium-scale TID's, which are listed in Table 6 along with some of their pertinent characteristics. Figure 29(a) shows a switchback between 0400 and 0500 UT with good visual correlation between the traces. This event clearly is seen over the Seward path before its appearance on the Wildwood path. The same arrival sequence also applies to the switchbacks occurring right after 0600 in Figure 30. Here, however, the disturbance has changed its signature in traveling from the Seward to the Wildwood radio path. The dispersive nature of medium-scale TID's is even more evident in Figure 31.



**FIGURE 29 DOPPLER SPECTRA SHOWING (a) SWITCHBACK SIGNATURES, AND (b) MODULATION EFFECT IN THE DOPPLER TRACES BETWEEN 1600 AND 1700 UT. THE LETTERS W AND S DENOTE THE WILDWOOD AND SEWARD CHANNELS RESPECTIVELY.**

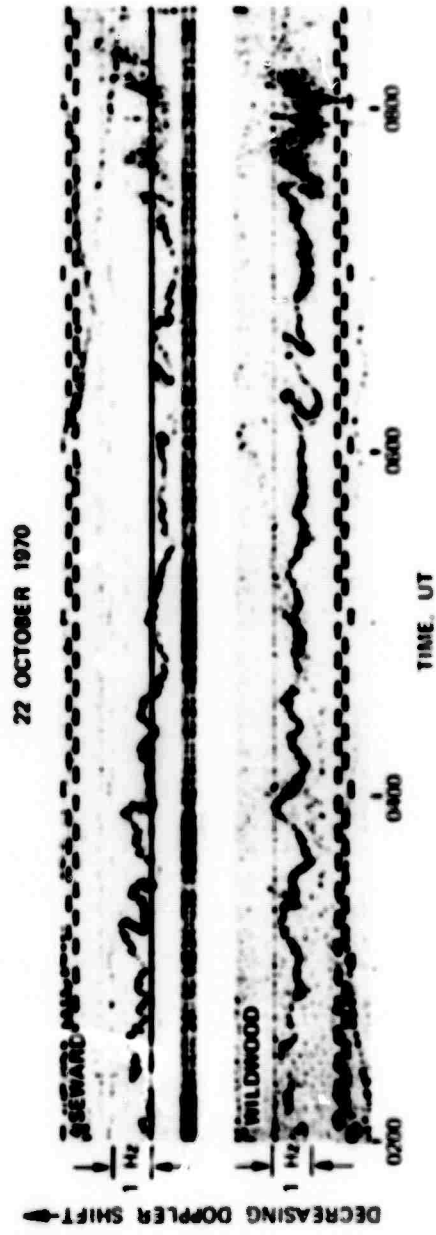


FIGURE 30 DOPPLER SPECTRA SHOWING SWITCHBACK SIGNATURES BETWEEN 0600 AND 0700 UT

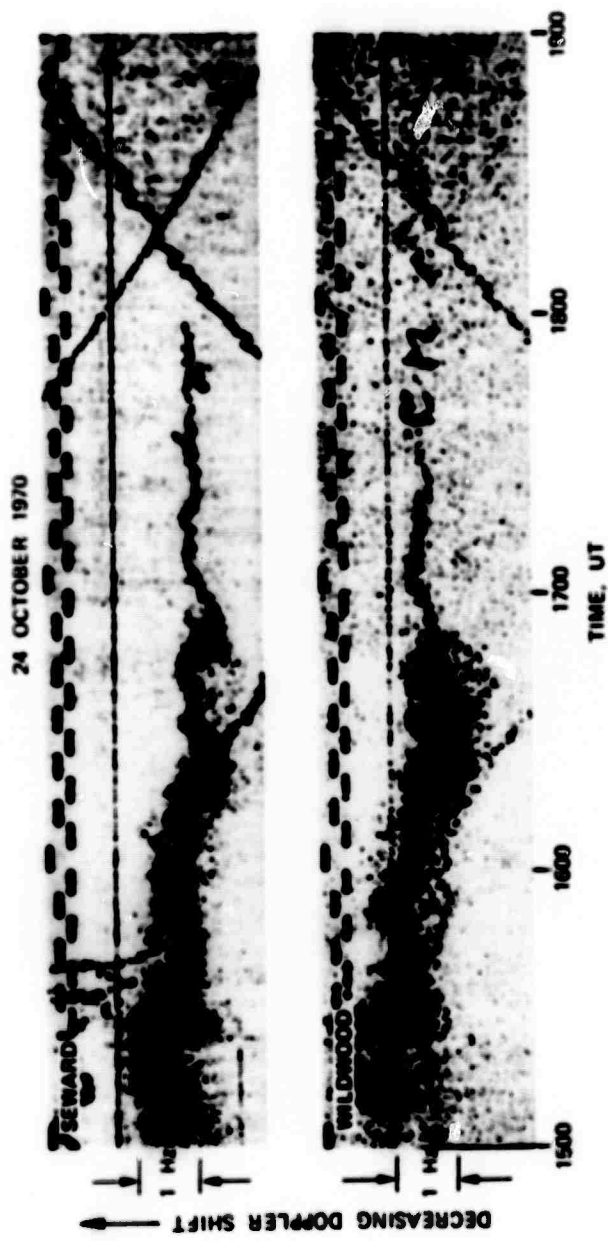


FIGURE 31 HIGHLY DISPERSIVE TID DETECTED ON THE SEWARD AND WILDWOOD PATHS

The disturbance that produced the distinctive "CM" signature prior to 1800 UT at Wildwood appears also on the Seward record, but has a very different appearance. These examples demonstrate some of the problems present in determining the velocities of TID's. When their features change as drastically as the example of Figure 31, an estimate is generally not possible.

When these TID's are compared with those depicted in Figures 25(a) and 28, one first notes that the two groups of TID's are quite different visually. For convenience, the TID's shown in Figures 25(a) and 28 will be referred to as Type A since their source seems to lie in the auroral region. The other group of TID's will be referred to as Type B.

Accurate travel directions of Type B TID's were not calculable because signals from only two paths were available. The arrival of the 21 and 22 October events at Seward before their arrival at Wildwood, however, indicates that the sources were to the east of the Homer network. Furthermore, assuming that medium-scale TID's have speeds of the order of 100 to 200 m/s, the time delays between the Seward and Wildwood traces (see Table 6) would require their direction of arrival to lie roughly along the line connecting the midpoints of the Seward-Homer and the Wildwood-Homer radio paths (see Figure 18).

Thus, the above would suggest that the sources of the Type-B TID's do not lie within the polar region. If this is true, then it is possible that these TID's are related to meteorological activity. The possibility that some medium-scale TID's are related to the aurora while others are not may explain why the sources of the disturbances are still unknown today after two decades of study. Certainly at mid-latitude, conclusions based on direction of arrival would be confused by the presence of two types of events.

b. Very Large TID's

Because of the small spacing between stations in the Alaskan Doppler array, the high velocities associated with very large TID's cannot be accurately measured. At times, an event might be rejected as a TID if it appears to occur simultaneously at each station, when, in fact, a small time shift exists. In many cases, very large TID's are recognized because the large Doppler changes associated with them tend to distinguish them from the background noise.

The 16 and 18 November TID's listed in Table 6 are two such events. The first event does not show any time shift between the Seward and Wildwood paths, but it was classified as a TID because of its resemblance to the 18 November event, which occurred approximately 24 hours later and does show a time shift between the two paths. The latter event followed a magnetic storm, which began around 1500 UT. Although one might infer a connection between the storm and the 18 November TID, the 17 November TID occurred on a magnetically quiet day.

An example of a very large TID that appears to be related to geomagnetic activity is shown in Figure 32. Between 0530 and 0645 UT all three Doppler traces show a slow variation that appears to correlate with a similar change in the H component of the geomagnetic field. The sequential time delays between these signatures suggest that the event was caused by a disturbance that arrived from an azimuth of  $60^{\circ}$  to  $70^{\circ}$ , with a horizontal trace speed of 300 m/s.

Under the hypothesis that the TID source lies on the auroral oval, Figure 33 shows the appropriate geometry. If the TID was generated near the region common to the angle of arrival and to the position of the auroral oval at 0400 UT, it would, traveling at a speed of 300 m/s, arrive over the Alaskan array two to three hours later. This would mean that the above signatures should occur at about 0600 to 0700 UT, in agreement with the observations.



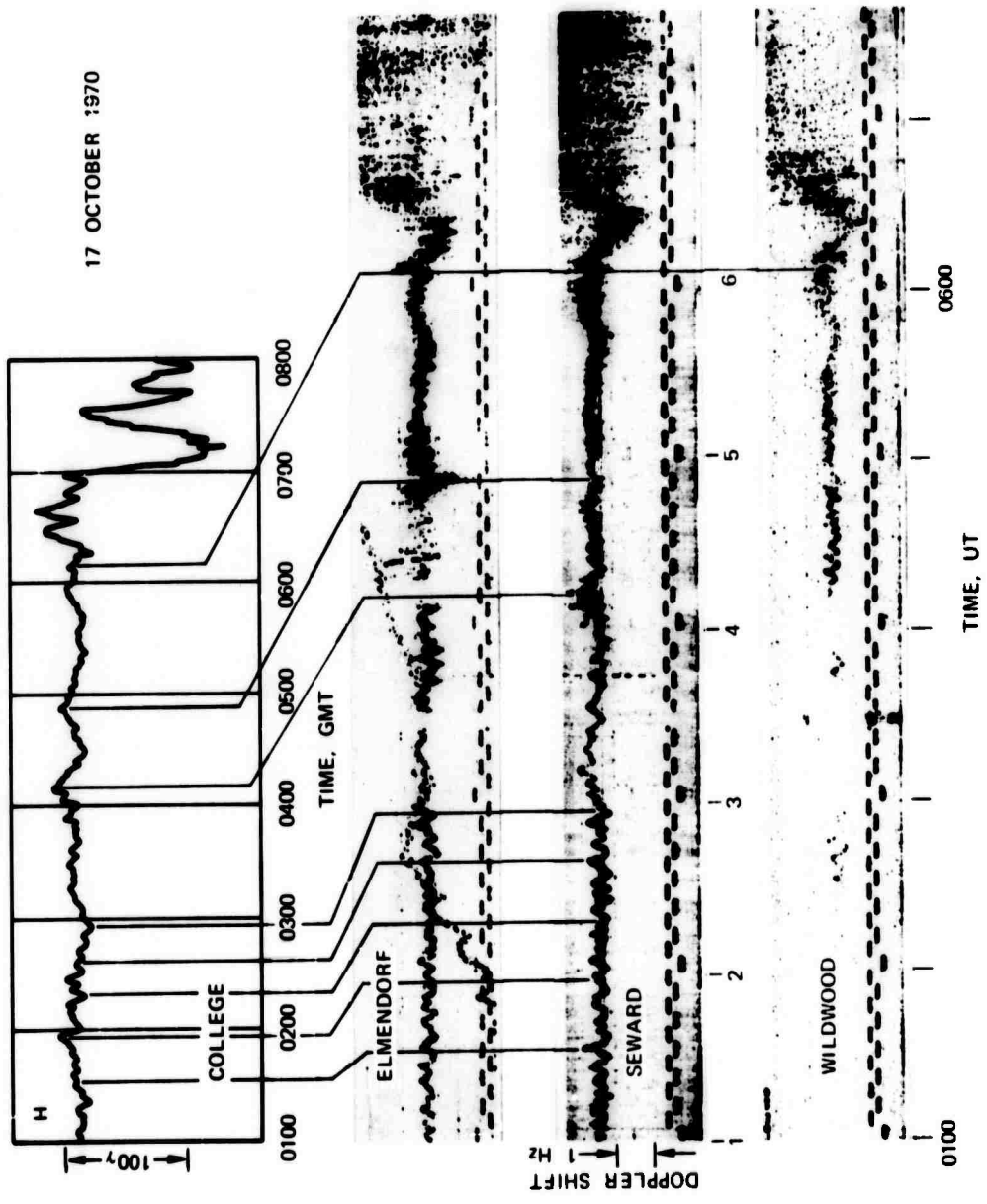
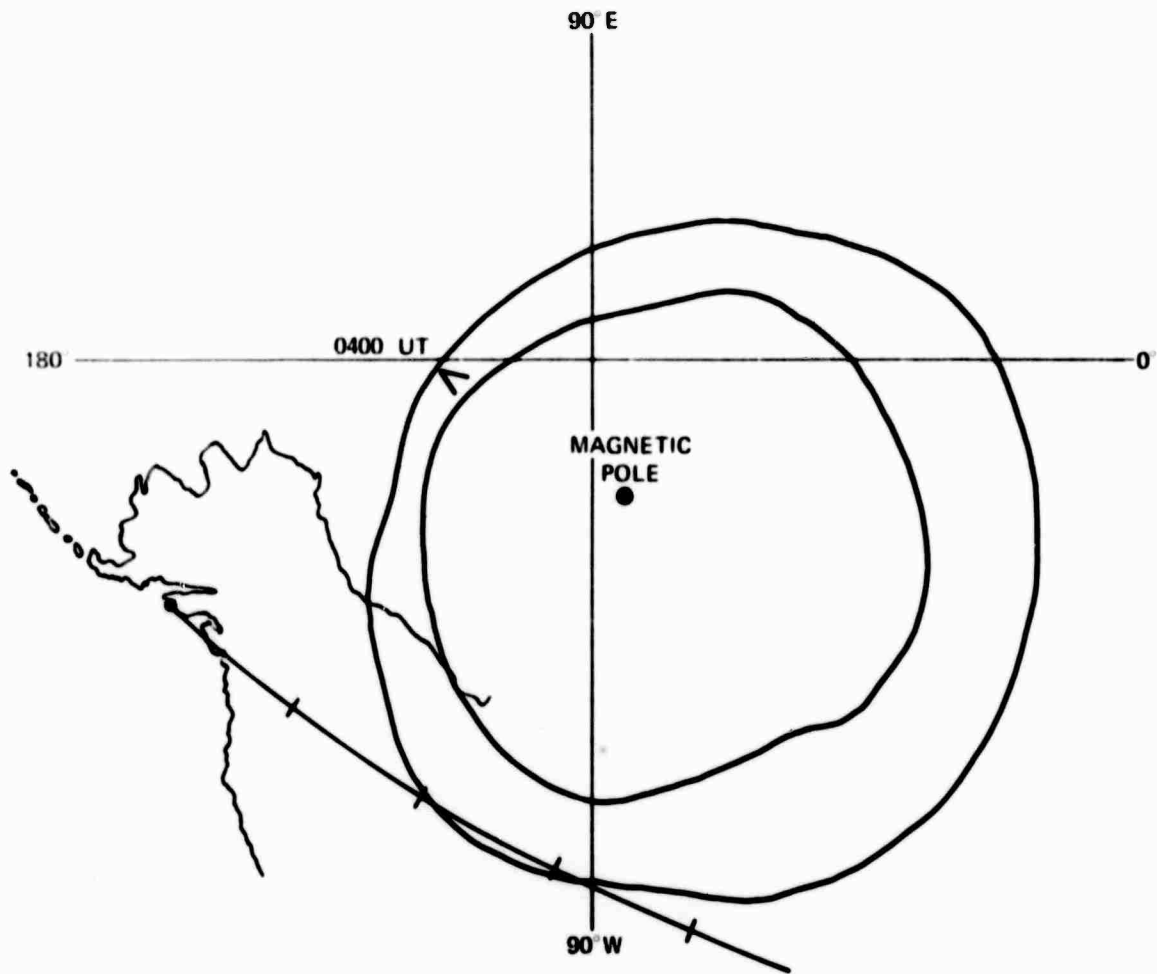


FIGURE 32 DOPPLER FLUCTUATIONS ASSOCIATED WITH GEOMAGNETIC VARIATIONS



**FIGURE 33 POLAR PROJECTION OF THE POSITION OF THE AURORAL OVAL AT 0400 UT AND THE CALCULATED DIRECTION OF ARRIVAL OF THE 17 OCTOBER 1970 TID**

Furthermore, if the above arguments are correct, the magnetic fluctuations that correlate with this event must have been produced by the passage of this disturbance over College. This follows, since any magnetic effect that is source-related should occur earlier in time (e.g., 0400 UT) and not when the disturbance was detected. A close inspection of the Doppler and magnetic records shows that there may be about a one-minute time shift between the magnetic-field variations and the Elmendorf Doppler trace. This shift is consistent with the travel direction and the velocity that were previously deduced.

The results described above, however, depend critically on whether these events are really TID's. With the broad trace on the Doppler records and time shifts that may be less than or equal to the limits of resolution, the chance of erroneously identifying an event as a TID is high. Since the Alaskan network was not intended to measure large-scale TID's, these uncertainties are unavoidable. The capabilities of the array to detect very large TID's, however, can be greatly enhanced with the simple addition of a receiving site at College. If the same transmissions--or preferably higher frequencies--were received, an independent array like that shown in Figure 13 would be formed. While this array in some sense would provide redundant information to the Homer network, reliability would increase and a measure of deviation in the measurements would be possible. For a southward-traveling TID, the 300-km spacing between the two networks would enable very large TID's to be detected readily.

## 2. Doppler Fluctuations Associated with Geomagnetic Variations

Doppler fluctuations with oscillation periods of a few minutes and with durations of tens of minutes or even hours are often associated with geomagnetic variations. Although events with periods as short as 20 seconds have been observed (Chang, 1969), they commonly have periods of a few minutes. The short-period events are readily detected on induction magnetometers, while the longer-period ones tend to be better revealed on standard magnetograms.

At times the rapid geomagnetic-related Doppler fluctuations resemble signatures associated with nuclear explosions (Baker and Cohen 1971), but they are easily distinguished from nuclear effects because (1) they have no measurable time displacements between features over two or more separated paths, (2) they show a high degree of correlation with geomagnetic variation, and (3) they have long durations. Doppler

fluctuations associated with nuclear explosions on the other hand (1) show an upward component of velocity (a horizontal velocity component has apparently never been measured by CW-Doppler observations due to the lack of suitable spaced transmissions), (2) are not related to geomagnetic variations, and (3) occur in a packet with a relatively short duration.

The association of phase-path changes with geomagnetic variations is not well understood. Lewis (1967) found that sudden impulses, and sudden commencements of geomagnetic storms always accompany rapid Doppler variations, but that the converse is not true. Three different models relating magnetic and Doppler fluctuation have been suggested by Duffus and Boyd (1968). These are given by Eq. (5), (6), and (7) in Table 4.

The first is a Hall drift model that relates changes in the ionization to current flow in the E region. The link from the E to F region is through electric fields. The second is a sudden commencement model that also involves motion of the ionization driven by an electric field. In this model, however, the electric field is produced by compression of the geomagnetic field caused by impinging solar matter. The third model involves collisional interaction with a traveling hydromagnetic or Alfvén wave. This is the Alfvén-wave model.

An example of an event where the oscillations in  $\Delta f$  correlate with similar changes in the H component of the magnetic field is illustrated in Figure 32. Note that while there is correlation, it is not perfect. A number of prominent fluctuations in H have no corresponding change in  $\Delta f$  and vice versa. Moreover, the magnitude of  $\Delta f$  does not seem to be as simply related to  $\Delta H$  as the above models suggest.

At least six clear cases of Doppler fluctuations that appear to be related to fluctuations in the geomagnetic field have been found during the observation period. Undoubtedly many more would have been detected if the system sensitivity were higher.

### 3. Newly Discovered Types of Events

The HF-Doppler data collected during the six-week observation period have revealed a number of interesting and unusual signatures. These events are distinguished in Figure 20 by a "U". Two of these events, discussed in detail in this section, are of particular interest because they apparently have not been previously observed at mid-latitude and thus may be unique to high latitudes.

Figure 34 shows an event that bears a strong resemblance to the post-sunset equatorial signatures shown in Figure 24. Near sunset, the equatorial records show a large dip in  $\Delta f$  due to an increase in the height of the F-layer. Shortly thereafter (2000-2400 UT), distinct traces that show a decreasing Doppler shift appear. These signatures finally merge with the main trace. On occasion they may extend slightly below the main trace ( $\Delta f < 0$ ), but they have never been observed with appreciable negative Doppler shifts.

The similarity between these signatures and those depicted in Figure 34 is striking. Like the equatorial records, the upward-sloping features near 0600 UT appear to be related to sunset. An important difference between this event and the equatorial events is that although both display Doppler shifts that decrease with time, the equatorial results generally show positive Doppler shifts, whereas the Doppler shifts of the 9 November event are negative.

This difference means that the disturbance responsible for the equatorial signatures caused the radio phase path to decrease with time, while Figure 34 indicates that the phase path was increasing with time. Furthermore, the split trace at Elmendorf suggests that two paths existed between this station and Homer. The trace marked "A" is apparently due to an off-great-circle path caused by the ionospheric disturbance. Trace "B", although somewhat broad, has little Doppler fluctuation and

9 NOVEMBER 1970

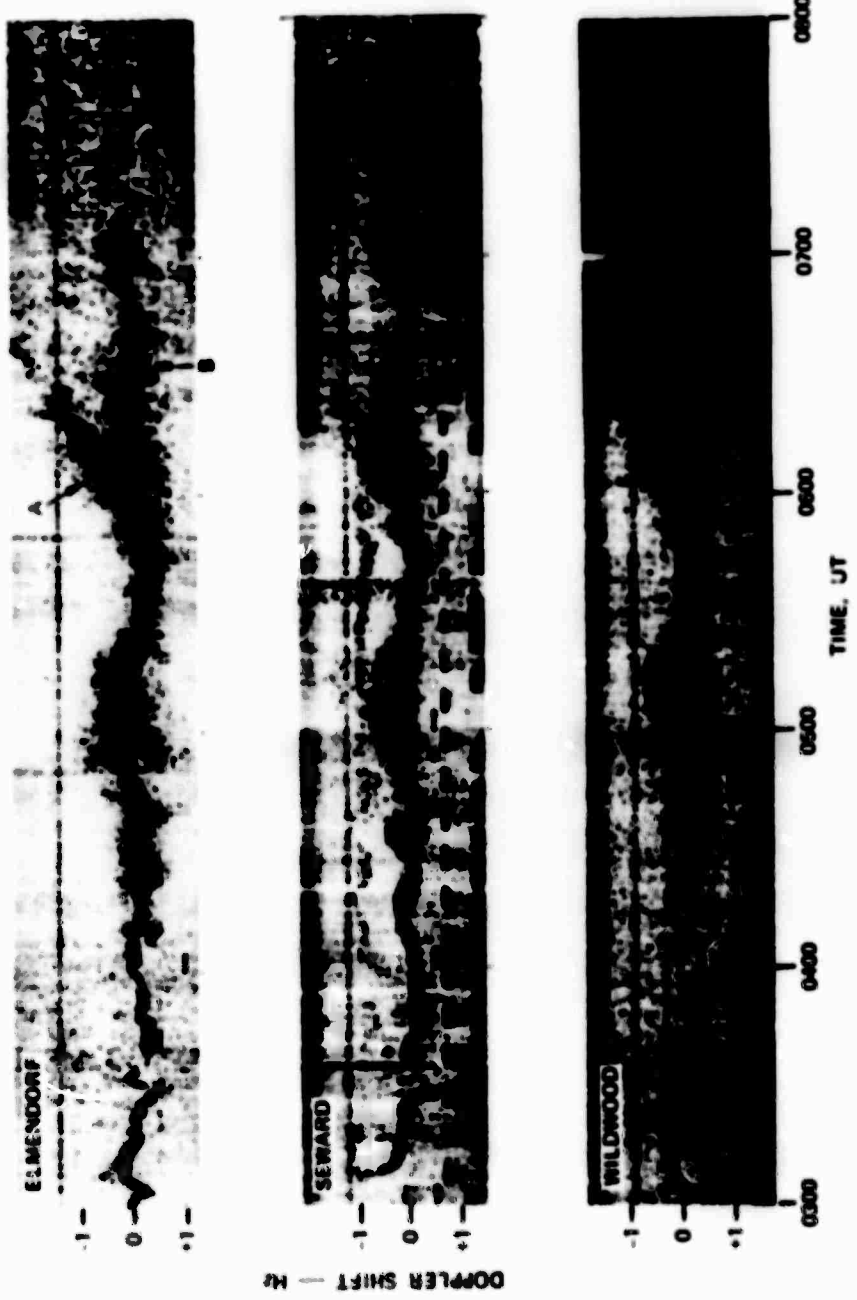


FIGURE 34 DOPPLER FLUCTUATIONS THAT RESEMBLE POST-SUNSET EQUATORIAL SIGNATURES

probably represents energy received over the undisturbed great-circle path. A similar but less distinct situation also exists for the Seward trace.

Magnetic activity at College was quiet from 0100 to 0800. Thus, this event does not appear to be related to local geomagnetic activity.

Because of the spread in the traces it is difficult to accurately determine the time shift that exists between the three traces of Figure 34. A careful measurement, however, revealed that the disturbance apparently occurred in the sequence Elmendorf, Seward, and Wildwood. Its direction of arrival was about  $54^{\circ}$  and it had a horizontal trace speed of about 250 m/s.

The equatorial signatures are believed to be caused by an asymmetrical reflecting surface with a sharp leading edge and a gradual trailing edge. As the surface moved toward the path midpoint, echoes with relatively large Doppler shifts are seen. As the surface passes overhead and away, only small Doppler shifts will be produced (Baker et al., 1968; Davies and Chang, 1968). A similar model can also explain the high-latitude signatures, but the reflecting surface must approach the path midpoint with the gradual edge leading. In this case large negative Doppler shifts will be produced as the surface passes overhead and recedes from the midpoint of the radio path.

The mechanism that could produce the asymmetrical surface proposed above is unknown, but since the high-latitude event occurs shortly after sunset, it seems reasonable to relate the source with sunset. A disturbance or instability may be caused by the passage of the terminator. This effect ultimately appears as the Doppler array in the form of a TID.

Another unusual event, which shows a modulation in the amplitude of its Doppler fluctuation, is shown in Figure 35. The envelope has a period of about 40 minutes and appears to vary in phase at the Seward and Wildwood paths. No structure was found within the envelope despite

20 OCTOBER 1970

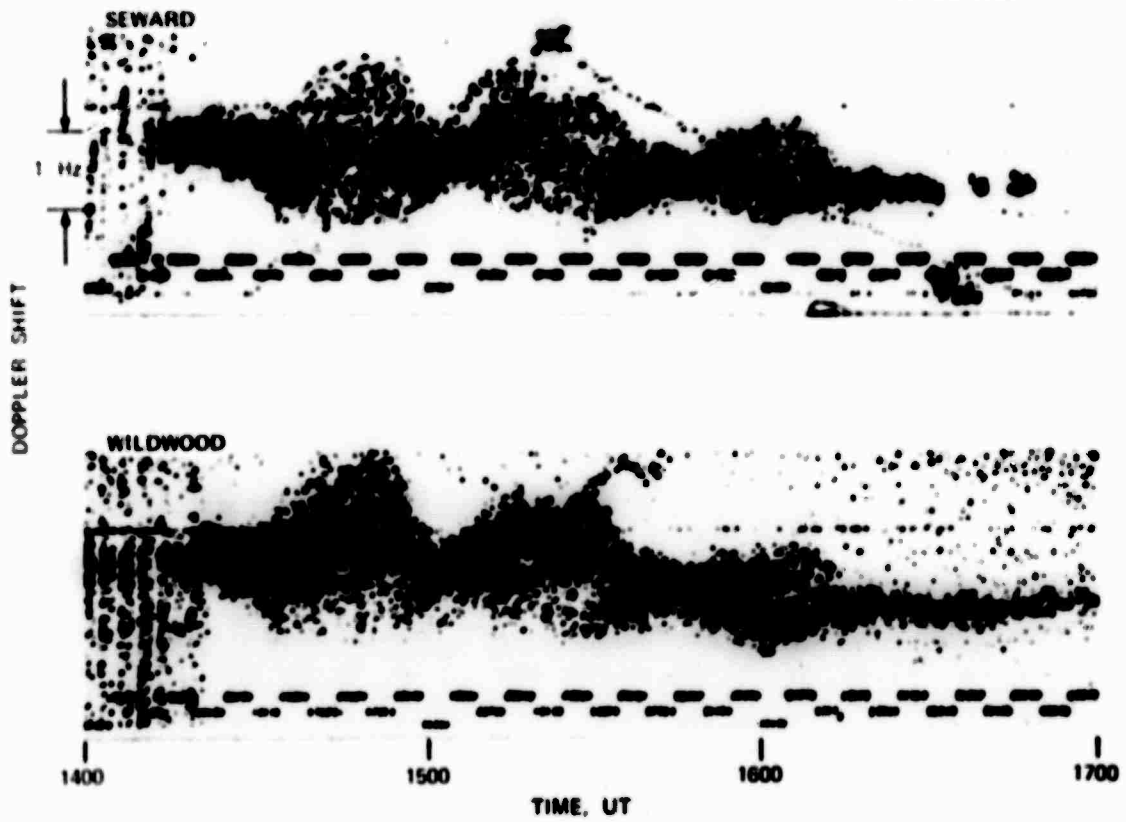


FIGURE 35 DOPPLER RECORDS SHOWING MODULATION IN THE SPECTRA

making various expanded replays of the data. The event began shortly after 1400 UT, although there are indications that it may have started an hour or two earlier but was obscured by interference.

This event does not appear to be related in any way to geomagnetic variations. Although the College magnetogram shows a disturbance beginning shortly after 0600 UT, with peak fluctuations of about 300  $\gamma$  in H (horizontal component of the geomagnetic field), the magnetic field was fairly quiet after 1200 UT. Inspection of the College induction magnetometer (measure of  $dH/dt$ ) shows rapid fluctuations of the order of tens of seconds, but nothing that can be related to the Doppler fluctuations of Figure 35.



On 21 October, a magnetically quiet day ( $\Sigma K_p = 2^-$ ), another modulated event occurred, as shown in Figure 29(b). The characteristics of its signature, however, differed from the 20 October event, and there is a possibility that the two events are unrelated. First, the modulation period of the 21 October event is about 20 minutes, in contrast to 40 minutes for the 20 October event. Second, there is a time shift in the envelope between Seward and Wildwood (indicating a horizontal component of velocity) plus a "phase" reversal in the envelope [feature between 1640 and 1700 in Figure 29(b)].

The lack of structure within the envelope and the symmetrical spread of the spectrum about the mean Doppler shift indicate that at a given time the scatterers were moving with random velocities such that there was no net change in the radio phase path. The cause of the perturbations is not known, but two possibilities are electron interaction with propagating waves (e.g., internal gravity waves) or impinging particles of unspecified origin.

In addition to the above, two other less distinct but nevertheless unusual signatures are also noted in Figure 20. These were observed on 9 and 10 November. On 9 November near 1000 UT (see Figure 36), a large positive Doppler shift occurred on all three traces. Although the nature of this signature suggests that the cause may be equipmental, the same signature 24 hours later tends to rule out this possibility.

There are apparently no time shifts between the three traces, but the diffuse traces make accurate measurements difficult. Thus if this signature was caused by a horizontally traveling disturbance, it had a high velocity. Alternatively, the disturbance could have been traveling predominantly in the vertical direction, with a nearly horizontal wavefront.



FIGURE 36 PORTION OF 9 NOVEMBER 1970 DOPPLER RECORDS SHOWING AN UNUSUAL DISTURBANCE NEAR 1000 UT

#### D. Relationship Between TID's and AIW's

The scarcity of Doppler data during the night when AIW occurrence is greatest makes it difficult to evaluate the relationship between TID's and AIW's. The disturbed magnetic conditions most conducive to AIW generation also produce a highly disturbed ionosphere. Thus, during days (22 October, 7 and 23 November in Figure 20) when many AIW's were observed at College, there is a corresponding lack of Doppler data. Although equipment improvement\* may permit Doppler observations to be made under these conditions, it is quite likely that the Alaskan network is too far north for effective nighttime observations.

If TID's and AIW's are generated at the same time and in the same general location, then, assuming that they have comparable velocities, one would expect to observe the occurrence of a TID at Homer about an hour or less after an AIW occurrence at College. Provided that the above assumptions are true, there are sufficient Doppler data on 22 October and 5 November to bracket four AIW's and thus possibly reveal any TID's that were concurrently generated.

No TID's were detected on 22 October that could be related to the two AIW's shown near 1600 UT in Figure 20. Figure 22(a) shows the occurrence of two AIW's at College in relation to the Doppler data. The Doppler spectra show no unusual fluctuations around the AIW that occurred at 1301 UT except for a distinctive signature at both Seward and Wildwood between 1000 and 1100 UT. Although this disturbance appears to occur simultaneously at each path, it may have been caused by a TID that had a high velocity and/or a wavefront parallel to the line connecting the reflection points of the Wildwood and Seward radio paths. However, since it occurred

---

\* An improvement of 13 dB can be readily achieved by decreasing the receiver bandwidth to about 100 Hz and by changing the transmitting antenna.

at Homer three hours prior to the AIW event at College, the two events are probably unrelated.

In addition to the sunrise effect and a short gap of data around 1600 UT, The Doppler spectrum shown in Figure 22(a) does not indicate any unusual signature that could be related to the 1625 UT AIW event. Prior to 1600 UT, Figure 22(b) shows a negative bay in H. Without more observations to provide a better picture of the diurnal pattern of  $\Delta f$ , little can be said regarding the relationship between the magnetic bay, the sunrise effect, the data gap around 1600 UT, and the AIW at 1625.

Wilson (1969a) has shown that AIW's are related to magnetic-bay activity caused by the auroral electrojet. At mid-latitudes the sunrise effect of Figure 22(a) is generally observed over oblique paths (see Figure 24) and is not related with magnetic activity. Since the near-vertical-incidence radio paths generally have sunrise effects like those shown in Figures 21 and 23, and not like the signature of Figure 22(a), there is a possibility that the disturbance around 1600 on the Doppler records, the magnetic bay, and the 1625 AIW are all related.

Figure 20 shows that in general TID occurrence is many hours removed from AIW occurrence. Out of 12 TID's indicated in Figure 20, only the 13 November event occurred within an hour of an AIW event. Thus, the different diurnal occurrence patterns of the two types of events would suggest that TID's and AIW's are unrelated. This conclusion, however, cannot be considered definitive since TID's may have gone undetected at night due to observational selection, such as the propagation conditions previously described (Spread-F).

The latter possibility is suggested because there are indications that TID's may occur at night without being detected by phase sounders. The basis of this statement is the similarity between TID occurrence

patterns at high- and mid-latitudes. If these patterns are source-related, then it is difficult to explain their similarity since the travel times from a source in the polar region to the Alaskan network or to a mid-latitude site differ by several hours or more. The predominance of daytime TID's in the Alaskan data, however, can readily be attributed to reduced sensitivity at night due to ionospheric chemistry or to differences between the day and night ionospheric gradients (Georges, 1967).

**BLANK PAGE**

## V CONCLUSIONS

A number of interesting results have been obtained during the course of this research, as described in detail in Sections III and IV. They permit some conclusions on the relationship between radar aurora and Auroral Infrasonic Waves (AIW's) and on generation of Traveling Ionospheric Disturbances at high latitudes. The more striking results, however, have perhaps been the totally unanticipated ones. These include identification of the radar signature of the poleward-expansion phase of auroral substorms and the discovery of several new types of ionospheric disturbances.

Regarding the radar aurora and AIW's, the work tends to reinforce a conclusion from earlier, statistical work (Fremouw, 1970) that the two phenomena are related in a general sense. AIW's do arise at times of and from regions of strong, bright, active radar auroras. The attempt to identify individual AIW sources with the auroral radar, however, has yielded only suggestive--not conclusive--results. The state of knowledge on the question is that AIW's usually are preceded by southward motion of apparently rapid auroral-radar backscattering regions, but that the observed motions are not necessarily followed by AIW's.

There is reason to believe that the preponderance of apparently rapid radar-auroral motions over the occurrence of AIW's is due, at least in part, to instrumental limitations in the present Homer radar. With the antenna fixed in position, as it was in the observations described herein, arc-like backscattering regions can display range rates relative to the radar that are considerably greater than their forward velocity, as described near the end of Section III-C. Thus, subsonic forms may be misinterpreted as supersonic ones that might be expected to produce AIW shocks. On the other hand, attempts to describe rapidly moving forms

more fully and more accurately by performing antenna scans are only rarely successful because of the time required for scanning mechanically.

In this regard, it should be pointed out that a radically different kind of auroral radar--offering vastly increased scan rates--is currently under design for the Homer site. This new instrument will be a 398-MHz, phased-array radar and is expected to be ready for operation at Homer late in 1972 (Chesnut et al., 1971). The phased-array antenna will have a 70-ft aperture and will be fully steerable mechanically, with a mechanical scan time on the order of a minute.

Far more important for studies of rapidly moving radar auroras of the type of interest for AIW research, however, will be the phased-array antenna's electronic scan capability. It will be possible to steer the radar beam electronically throughout a 20-degree cone (i.e.,  $\pm 10^\circ$  from the mechanical boresight) in about a second. In addition, a variety of beam shapes will be possible by means of computer phasing of array elements. The computer also will control data formatting and provide a real-time data-processing capability.

In view of the limitations of the present Homer instrumentation for performing the rapid, high-resolution search needed for isolating AIW sources, and the order-of-magnitude improvement anticipated in 1972, a moratorium on the search is suggested. Resumption of the search in late 1972 or early 1973 with the world's first phased-array auroral radar should prove fruitful, in the light of present knowledge.

The most definitive result of the radar studies carried out in the current program was discovery of the poleward-expansion radar signature. These echoes from rapidly receding radar backscattering regions clearly are the radar signature of the poleward-expansion phase of the polar magnetic substorm. The radar auroral forms identified move northward, away from Homer, with range rates of several hundred to a few thousand



meters per second (800 m/s to 2 km/s in the seven events studied to date), and bear a one-to-one relationship with similar explosive motions in the visual aurora and with abrupt beginnings of negative bays in the geomagnetic field. Further studies of this phenomenon should contribute to understanding of the dynamics of substorm development.

The radar-auroral poleward expansions have significance for AIW research. Not one of the seven such events noted in the present work was accompanied by an AIW shock front even though all appeared to be supersonic (i.e., displayed range rates in excess of 300 m/s). On the other hand, many radar auroras moving southward toward the radar with even smaller range rates were followed by AIW's (although not all, as described in Section III-C). This set of circumstances is consistent with Wilson's model (private communication) for AIW generation by Pedersen drift of ions in the auroral E-layer. In this model, auroral arcs containing westward electrojets (which produce negative magnetic bays) should produce AIW's when they move southward supersonically, but not when they move northward at similar velocities.

Unlike the radar-aurora/AIW research reported herein, the TID research constituted a pilot program. Its first goal was to establish whether TID's could be observed with the HF-Doppler sounding technique in the Homer vicinity, just equatorward of the possible source region in the auroral oval. Such observations were, in fact, made.

For the most part, the HF-Doppler records obtained showed spread spectra at night and particularly under aurorally disturbed conditions. This reduces the likelihood of observing TID's generated locally (i.e., in Alaska) by nighttime auroral disturbance and the accuracy with which characteristics of such TID's could be scaled, making direct comparison with locally generated AIW's difficult. The spectral spread, however, does not totally preclude observation of TID's at night.

Notwithstanding the above condition, the Homer site was found in general to be an excellent location for TID studies. Unusually long trains of medium-scale TID's were observed arriving from the north, probably from within the auroral oval and quite possibly from the midnight sector. Another group of medium-scale TID's was found that did not appear to originate from the auroral or the polar region. The observation of two classes of medium-scale TID's at Homer may account for long-standing confusion in the interpretation of mid-latitude TID observations.

It is possible that one of the two classes of medium-scale TID's observed at Homer is of meteorological origin and the other of auroral origin, but the current data base is insufficient to test this hypothesis. It is strongly suggested that longer-term observations be performed at the Homer site in order to study the morphological characteristics of high-latitude TID's. The first priority of such a study should be to determine the diurnal variation of arrival direction, for comparison with that expected for a source located in the midnight sector of the auroral oval. If such a source exists, it should be possible to "track" its motion around the geomagnetic pole by means of observations at Homer.

In addition to medium-scale TID's, several other types of interesting F-layer disturbances were observed in the present program. They included one type that appeared to consist of very large TID's, which traveled past the array at high velocity, and another previously recognized type associated with geomagnetic variations. Beyond these, however, two unusual events were noted that may represent newly discovered phenomena; so far as is known they are unique to the high-latitude observations carried out at Homer in the present program.

In summary, the research reported herein (1) is consistent with the view that Auroral Infrasonic Waves (AIW's) result from Pedersen drift of ions associated with equatorward-propagating supersonic arcs, although

it is not definitive on this point; (2) has yielded identification of an auroral-substorm radar signature; and (3) has demonstrated the feasibility of observing Traveling Ionospheric Disturbances (TID's) at a high-latitude (subauroral) site. More detailed observations with a planned 398-MHz, phased-array, auroral radar and longer-term HF-Doppler observations are suggested as means of further understanding AIW's, TID's, and related ionospheric phenomena important to geoaoustic research.

**BLANK PAGE**

#### REFERENCES

- Agy, V., D. M. Baker, and R. M. Jones, "Studies of Solar Flare Effects and Other Ionospheric Disturbances with a High Frequency Doppler Technique," NBS Technical Note 306 (1965).
- Baker, E.C., and J. A. Gledhill, "An Unusual Traveling Disturbance in the F Region of the Ionosphere," J. Atmos. Terr. Phys., Vol. 27, pp. 1223-1227 (1965).
- Baker, D. M., N. Chang, K. Davies, R. F. Donnelly, and J. E. Jones, "A Review of Some Ionospheric Studies Based on a High-Frequency Doppler Technique," ESSA Technical Report ERI 78-SDI 1, U.S. Government Printing Office, Washington, D.C. (1968).
- Baker, D. M., and D. E. Cohen, "Interpretation of High-Frequency Doppler Observations of Waves from Nuclear and Natural Sources," J. Geophys. Res., Vol. 76, pp. 1803-1810 (1971).
- Basler, R. P., "Radio Wave Absorption in the Auroral Ionosphere," J. Geophys. Res., Vol. 68, pp. 4665-4681 (1963).
- Bowman, G. G., "Traveling Disturbances Associated with Ionospheric Storms," J. Atmos. Terr. Phys., Vol. 27, pp. 1247-1261 (1965).
- Bowman, G. G., "Extremely Large Traveling Ionospheric Disturbance in Antarctica," Scientific Report, AVCO Missile, Space and Electronics Group (1967).
- Chan, K. L., and O. G. Villard, Jr., "Observation of Large-Scale Traveling Ionospheric Disturbances by Spaced-Path High-Frequency Measurements," J. Geophys. Res., Vol. 67, pp. 973-988 (1962).
- Chang, N.J.F., "Acoustic-Gravity Waves in the Ionosphere and Their Effects on High-Frequency Radio Propagation," Ph.D Thesis, University of Colorado, Boulder, Colorado (1969).
- Chesnut, W. G., R. I. Presnell, and J. C. Hedges, "Project 609 Auroral Environment Research for DASA Auroral SAT Program," Experiment Plan, Stanford Research Institute, Menlo Park, California (1971).

REFERENCES (continued)

- Chimonas, G., and C. G. Hines, "Atmospheric Gravity Waves Launched by Auroral Currents," Planet. Space Sci., Vol. 18, pp. 565-582 (1970).
- Chrzanowski, P., G. Green, K. T. Lemmon, and J. M. Young, "Traveling Pressure Waves Associated with Geomagnetic Activity," J. Geophys. Res., Vol. 66, pp. 3727-3733 (1961).
- Cole, K. D., "A Source of Energy for the Ionosphere," Nature, Vol. 194, p. 75 (1962).
- Davies, K., J. M. Watts, and D. H. Zacharisen, "A Study of F<sub>2</sub>-layer Effects as Observed with a Doppler Technique," J. Geophys. Res., Vol. 67, pp. 601-609 (1962).
- Davies, K., and D. M. Baker, "On Frequency Variations of Ionospherically Propagated HF Radio Signals," Radio Sci., Vol. 1, pp. 545-556 (1966).
- Davies, K., and N.J.F. Chang, "Radio-Doppler Observations of the Ionosphere near the Magnetic Equator," in Scatter Propagation of Radio Waves, AGARD Conference Proceedings 37, Part 2, Paper 52 (1968).
- Davies, K., and J. E. Jones, "Three-Dimensional Observations of Traveling Ionospheric Disturbances," J. Atmos. Terr. Phys., Vol. 33, pp. 39-46 (1971).
- Davis, M. J., and A. V. da Rosa, "Traveling Ionospheric Disturbances Originating in the Auroral Oval During Polar Substorms," J. Geophys. Res., Vol. 74, pp. 5721-5735 (1969).
- Donnelly, R. F., "The Solar Flare Radiations Responsible for Sudden Frequency Deviations," J. Geophys. Res., Vol. 72, pp. 5247-5256 (1967).
- Duffus, H. J., and G. M. Boyd, "The Association Between ULF Geomagnetic Fluctuations and Doppler Ionospheric Observations," J. Atmos. Terr. Phys., Vol. 30, pp. 481-496 (1968).
- Elkins, T. J., and F. F. Slack, "Observations of Traveling Ionospheric Disturbances Using Stationary Satellites," J. Atmos. Terr. Phys., Vol. 31, pp. 421-439 (1969).

REFERENCES (continued)

- Fremouw, E. J., "Radar Investigations of Auroral Infrasonic Wave Sources," Annual Report, Contract F44620-69-C-0074, SRI Project 78-10, Stanford Research Institute, Menlo Park, California (1970).
- Georges, T. M., "Ionospheric Effects of Atmospheric Waves," ESSA Technical Report IER 57-1TSA 54, U.S. Government Printing Office, Washington, D.C. (1967).
- Georges, T. M., "HF Doppler Studies of Traveling Ionospheric Disturbances," J. Atmos. Terr. Phys., Vol. 30, pp. 735-746 (1968).
- Goodwin, G. L., "Some Horizontally Moving Ionospheric Irregularities at High Latitudes," Planet. Space Sci., Vol. 16, pp. 273-283 (1968).
- Heisler, L. H., "Anomalies in Ionosonde Records due to Traveling Ionospheric Disturbances," Australian J. Phys., Vol. 11, p. 79 (1958).
- Heisler, L. H., "Observation of Movement of Perturbations in the F-Region," J. Atmos. Terr. Phys., Vol. 25, pp. 71-86 (1963).
- Hines, C. O., "Internal Atmospheric Gravity Waves at Ionospheric Heights," Can. J. Phys., Vol. 38, pp. 1441-1481 (1960).
- Hunsucker, R. D., and L. H. Tveten, "Large Traveling-Ionospheric Disturbances Observed at Mid-Latitudes Utilizing the High Resolution HF Backscatter Technique," J. Atmos. Terr. Phys., Vol. 29, pp. 909-916 (1967).
- Jones, J. E., "Observation of Traveling Ionospheric Disturbances by the Doppler Technique with Spaced Transmitters," ESSA Technical Report ERI 142-SDI 11, U.S. Government Printing Office, Washington, D.C. (1969).
- Jones, J. E., "Observation of Ionospheric Disturbances in Antarctica During 1968," ESSA Technical Report ERI 153-SDI 12, U.S. Government Printing Office, Washington, D.C. (1970).
- Klostermeyer, J., "Gravity Waves in the F-Region," J. Atmos. Terr. Phys., Vol. 31, pp. 25-45 (1969).
- Lewis, T. J., "The Association of Phase Changes of Ionosphere-Propagating Radio Waves and Geomagnetic Variations," Can. J. Phys., Vol. 45, pp. 1549-1563 (1967).

REFERENCES (continued)

- Laffie, D. A., "Post Sunset Effects in the Equatorial Ionosphere," NBS Report 8178, U.S. Department of Commerce, National Bureau of Standards, Boulder, Colorado, pp. 82-98 (1964).
- Liszka, L., and G. N. Taylor, "A Synoptic Study of Large-Scale Ionospheric Irregularities Using Observations of the Faraday Rotation of Satellite Signals," J. Atmos. Terr. Phys., Vol. 27, pp. 843-854 (1965).
- Maeda, K., and T. Watanabe, "Pulsating Aurorae and Infrasonic Waves in the Polar Atmosphere," J. Atmos. Sci., Vol. 21, pp. 15-29 (1964).
- Munro, G. H., "Traveling Disturbances in the Ionosphere," Proc. Roy. Soc., Vol. A 202, pp. 208-223 (1950).
- Munro, G. H., "Reflexions from Irregularities in the Ionosphere," Proc. Roy. Soc., Vol. A 219, pp. 447-462 (1953).
- Munro, G. H., "Traveling Ionospheric Disturbances in the F-Region," Australian J. Phys., Vol. 11, pp. 91-112 (1958).
- Munro, G. H., and L. H. Heisler, "Cusp Type Anomalies in Variable Frequency Ionospheric Records," Australian J. Phys., Vol. 9, pp. 343-358 (1956a).
- Munro, G. H., and L. H. Heisler, "Divergence of Radio Rays in the Ionosphere," Australian J. Phys., Vol. 9, pp. 359-372 (1956b).
- Piddington, J. H., "An Ionization Drift Theory of Aurora and Airglow," Geophys. J. Roy. Astron. Soc., Vol. 7, p. 415 (1963).
- Piddington, J. H., "Geomagnetic Storms, Aurorals, and Associated Effects," Space Sci. Rev., Vol. 3, pp. 724-780 (1964).
- Price, R. E., "Traveling Disturbances in the Ionosphere," Report of the Physical Society Conference on Physics of the Ionosphere, London, September, 1954, pp. 181-190 (1954).
- Thomas, L., "Some Measurements of Horizontal Movements in F2-Region Using Widely Spaced Observing Stations," J. Atmos. Terr. Phys., Vol. 14, pp. 123-137 (1959).



REFERENCES (continued)

- Thome, George D., "Incoherent Scatter Observation of Traveling ionospheric Disturbances," J. Geophys. Res., Vol. 69, pp. 4047-4049 (1964).
- Thome, George D., "Long-Period Waves Generated in the Polar Ionosphere During the Onset of Magnetic Storms," J. Geophys. Res., Vol. 73, No. 19, pp. 6319-6336 (1968).
- Titheridge, J. E., "Periodic Disturbances in the Ionosphere," J. Geophys. Res., Vol. 73, pp. 243-252 (1968).
- Vasseur, G., and P. Waldteufel, "Thomson Scatter Observations of a Gravity Wave in the Ionospheric F-Region," J. Atmos. Terr. Phys., Vol. 31, pp. 885-888 (1969).
- Watts, J. M., and K. Davies, "Rapid Frequency Analysis of Fading Radio Signals," J. Geophys. Res., Vol. 65, pp. 2295-2301 (1960).
- Whitehead, J. D., "The Focusing of Short Radio Waves Reflected from the Ionosphere," J. Atmos. Terr. Phys., Vol. 9, pp. 269-275 (1956).
- Wickersham, A. F., Jr., "Identification of Ionospheric Motions Detected by the High-Frequency Backscattering Technique," J. Geophys. Res., Vol. 69, pp. 457-463 (1964).
- Wickersham, A. F., Jr., "Comparison of Velocity Distributions for Acoustic-Gravity Waves and Traveling Ionospheric Disturbances," J. Geophys. Res., Vol. 70, pp. 4875-4883 (1965).
- Wickersham, A. F., Jr., "Identification of Acoustic-Gravity Wave Modes from Ionospheric Range-Time Observations," J. Geophys. Res., Vol. 71, pp. 4551-4555 (1966).
- Wilson, C. R., "Infrasonic Pressure Waves from the Aurora: A Shock Wave Model," Nature, Vol. 216, pp. 131-133 (1967).
- Wilson, C. R., "Auroral Infrasonic Waves," J. Geophys. Res., Vol. 74, pp. 1812-1836 (1969a).
- Wilson, C. R., "Infrasonic Waves from Moving Auroral Electrojets," Planet. Space Sci., Vol. 17, pp. 1107-1120 (1969b).

END