Artificial Ionospheric Irregularities Measured with MUIR (Modular UHF Ionospheric Radar) at HAARP (High Frequency Active Auroral Research Program)

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Plasma physics is widely applied in space research, and has become a fundamental field of study, much like the fields of thermodynamics and electromagnetism. As natural phenomena, the ionosphere and magnetosphere generate and absorb plasma waves. While the science of naturally enhanced plasma waves is important to understand ionospheric/magnetospheric phenomena, artificially enhanced plasma waves also provide notable information that can help advance our understanding of both space physics and plasma physics. Many experiments on the modification of the ionosphere with high-power, high-frequency (HF) radio waves have been conducted since the 1970s. HAARP (High Frequency Active Auroral Research Program) facility in Gakona, Alaska has played important roles in this field. MUIR (Modular UHF Ionospheric Radar; 446 MHz) began operation at HAARP in February 2005. The main advantage of this radar is that its phased array system allows the beam direction to be quickly changed. The radar has been used to obtain important data sets during many HF ionospheric modification experiments. In this paper we present our findings regarding (1) HF-induced ion lines and plasma lines, (2) overshoot, and (3) Langmuir wave generation in the first 100 ms after HF turn-on.

1 Introduction

Many experiments on the modification of the ionosphere with high-power, high-frequency (HF) radio waves have been conducted since the 1970s. The world's major HF facilities are (were) the Arecibo observatory, Puerto Rico (the Arecibo facility, 18.35˚N, 66.75˚W was operated from 1971 to 1978, and the Islote facility, 18.48˚N, 66.66˚W, was operated from 1981 to 1998), the European Incoherent Scatter (EISCAT) Tromsø site, Norway (69.59˚N, 19.23˚E), the Space Plasma Exploration by Active Radar (SPEAR) at Svalbard, Norway (78.15˚N, 16.05˚E), HF Active Auroral Research Program (HAARP) in Gakona, Alaska (62.39˚N, 145.1˚W), the High Power Auroral Stimulation (HIPAS) observatory near Fairbanks, Alaska (64.87˚N, 146.84˚W), the Sura Facility near Vasil'sursk, Russia (56.13˚N, 46.10˚E), Kharkov observatory, Ukraine (50.00˚N, 36.20˚), and the Platteville, Colorado observatory (operated from 1970 to 1981, 40.18˚N, 104.73˚W). Only three—at Arecibo, Tromsø, and Svalbard—have powerful incoherent scatter (IS) radars. The Arecibo radar operates at a center frequency of 430 MHz, the two EISCAT IS radars at Tromsø operate at frequencies near 224 MHz and 931 MHz, and the one at Svalbard operates at 500 MHz. The scale of the ionospheric irregularities observed with the IS radar becomes smaller as the radar transmitting frequency increases. Since HF-induced plasma waves tend to be aligned with the magnetic field line, the angle difference between the IS radar beam direction and the magnetic field line determines the key feature of the plasma wave observed with the IS radar. This is called aspect sensitivity. Since the magnetic dip angle becomes larger at higher latitudes, the characteristics of observed plasma waves also depend on the radar location. At the Arecibo facility the dip angle is relatively small (~40°) because of the low latitude. Thus, the radar mainly observes plasma waves propagating transverse to the magnetic field line. On the other hand, the IS radars at Norway can measure plasma waves along the magnetic field line because they are located at high latitudes and the dip angle is close to 90°.

Ionospheric artificial modification experiments offer advantages compared to laboratory experiments using vacuum chambers. First, there is no chamber wall in the ionosphere. No assumptions regarding the wall are necessary, and an ideal experiment space can be prepared in the ionosphere. Second, experiments can be done under various conditions regarding plasma density, temperature, geomagnetic amplitude, and so on. For example, many experiments have been conducted when Polar Mesosphere Summer Echoes (PMSE) and the sporadic E-layer appeared. These experiments have contributed to interdisciplinary studies through applications of plasma-wave theory to ionospheric phenomena.

In the many artificial ionospheric modification experiments that have been done, the selection of appropriate diagnostic instruments has always been an important issue. The IS radar is a representative powerful diagnostic instrument [Showen and Kim, 1978; Hagfors et al., 1983; Stubbe et al., 1985; Duncan and Sheerin, 1985; Djuth et al., 1986; Cheung et al., 1989; Djuth et al., 1990; Cheung et al., 1992; Isham and Hagfors, 1993; Djuth et al., 1994; Isham et al., 1999; Rietveld et al., 2000]. The IS radar detects the Langmuir wave. The HF pump wave generates various plasma waves including the Langmuir wave through parametric decay instability (PDI) and oscillating two-stream instability (OTSI) [e.g., Fejer and Kuo, 1973; Perkins et al., 1974]. The IS-radar measurement allows us to investigate, for example, generation and propagation processes of the Langmuir wave using data with high altitude/time resolutions.

Figure 1 shows time developments of spectra (color panels) deduced through spectrum analysis of the backscatter echo measured with MUIR for 1 s, and the processes of plasma-wave generation. The electromagnetic wave (EM_0, pump wave; as shown in the figure) transmitted from the high-power HF antenna generates the Langmuir wave (LW) in the modified ionosphere. The generated Langmuir wave propagates, producing other Langmuir waves; these are called daughter waves and they oscillate at frequencies different from the original LW frequency. These by-product plasma waves can be identified as several spectrum peaks that appear in the ion and plasma lines detected with the IS radar. One is the ion acoustic peak in the ion line (middle color-panel in Fig. 1). The ion acoustic peak shifts from f_{radar} (radar pulse frequency) by the ion acoustic frequency towards the higher and lower frequency sides. Another peak may be observed at f_{radar} through OTSI.

Other spectrum peaks associated with the daughter waves can be seen in the plasma line. There are two kinds of plasma line: one is the up-shifted plasma line (top color-panel), which appears on the higher frequency side from f_{radar}, and the other is the down-shifted plasma line (bottom color-panel). The up- and down-shifted plasma lines are due, respectively, to Langmuir waves propagating toward or away from the radar along the radar line-of-sight. One can see five (perhaps six) spectrum peaks appearing separately in the frequency domain. These peaks, except for the first peak near $f_{radar} \pm f_{HF}$, where f_{HF} is the HF frequency, are called the cascade line. (The first peak is called the decay line.) The cascade line is the daughter-wave spectrum.

MUIR (Modular UHF Ionospheric Radar; f_{radar} = 446 MHz) was recently installed at HAARP. This radar is a development version

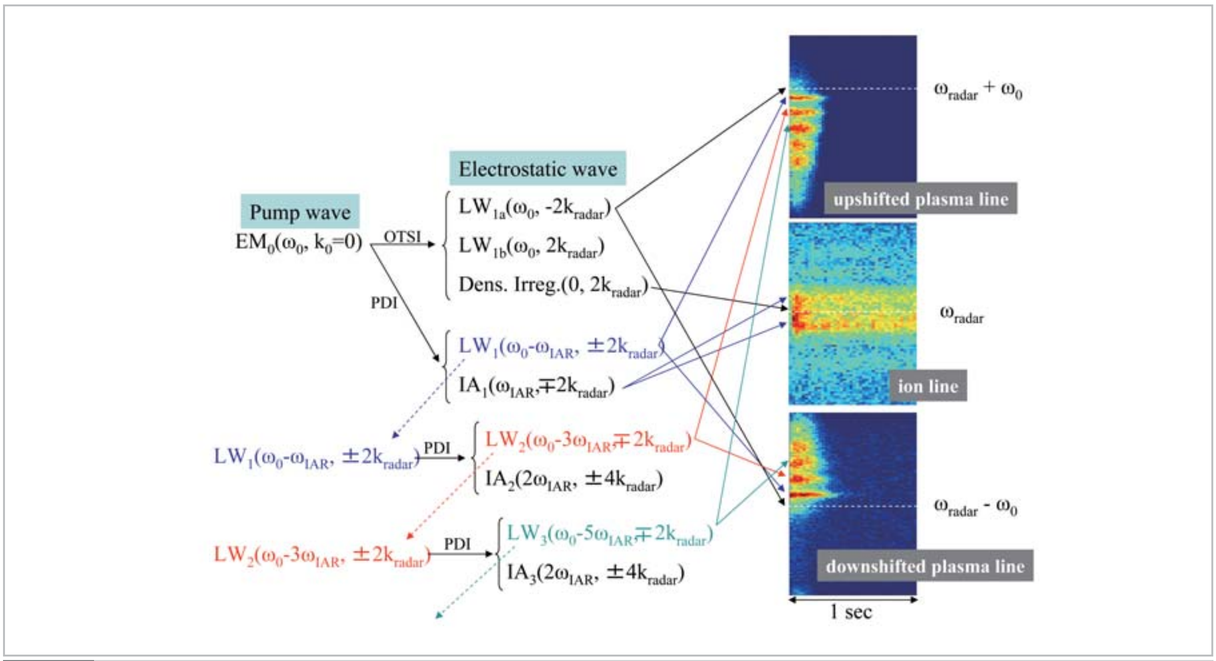

Fig. 1 *HF-induced up-shifted (top right panel) and down-shifted (bottom right panel) plasma lines and ion lines (middle right panel) measured with MUIR during HF modification experiment*

The x-axis shows relative time after HF turn-on, and the y-axis shows the offset frequency for each line. Horizontal dotted lines are shown at the frequency of the radar frequency plus/minus the HF frequency for the up/down-shifted plasma line, respectively, and the radar frequency for the ion line. Development of the plasma wave through parametric decay instability (PDI) and oscillating two-stream instability (OTSI) is schematically illustrated at the left to show the excitation process of Langmuir oscillations and ion waves. Colored arrows with solid lines show correspondence between plasma waves (LW and IA) and spectrum peaks seen in the color panel.

of the AMISR (Advanced Modular Incoherent Scatter Radar) developed by the National Science Foundation and SRI International for incoherent scatter observation at polar northern America (details are given in the next section). The most notable advantage of this radar is the phased array system, which allows us to change the beam direction for every radar pulse transmission. This technique plays an important role in the study of the aspect sensitivity of plasma waves. The first ionospheric modification observations made with MUIR took place on 3 February 2005 [Oyama et al., 2006]. Many experiments have since been done and many significant scientific results obtained. This paper presents some of the results from recent observations.

2 Instrument

2.1 HAARP facility

The HAARP facility is located at Gakona, Alaska (about 5 hours driving distance from Anchorage or Fairbanks), and is operated by the Office of Naval Research (ONR) and Air Force Research Laboratory. Figure 2 shows a map of Alaska, with Gakona indicated by a yellow star. Various radio instruments (imaging riometer, digisonde, VLF receiver, VHF radar, HF receiver, etc.) and optical instruments (all-sky imager, photometer, etc.) are installed in the facility. Instruments installed at the Poker Flat Research Range near Fairbanks are also used to do simultaneous observations. An up-grade of the high-power HF transmitter system with large antenna arrays was completed by summer 2007, and HAARP is now the biggest facility in the world in terms of HF-

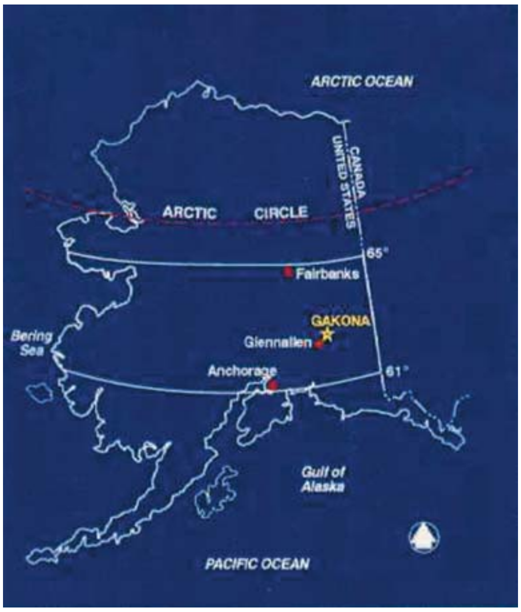

Fig.2 *Map of Alaska*

HAARP is located at Gakona, which is indicated by a yellow star.

Table 1 *Parameters of the HAARP high-power HF transmitting system*

Radiated Power	3600 kW
Frequency Coverage	2.8-10 MHz
Antenna Gain	20-31 dB
ERP	86-95 dBW
Antenna Beam Width	4.5°-15°
Beam Pointing Angle	30° from zenith @ all azimuth
Re-position Time	15 μs
Polarization	O/X, Linear
Modulation Types	AM/FM/Pulse/CW
Modulation Frequncy	0-30 kHz Generally

transmitting peak power (3600 kW) and available HF band width (2.8–10 MHz). Table 1 summarizes the system parameters. Figure 3 is an aerial photograph of the HAARP facility. The white poles seen in the center are HF transmitter antennae, and the operation room is in the white building behind the antenna array. While MUIR cannot be seen in this photograph, the radar is located to the right of the operation building.

Fig.3 *Aerial photograph of HAARP*

2.2 MUIR

MUIR (f_{radar} = 446 MHz) is operated with almost the same system as the AMISR (Advanced Modular Incoherent Scatter Radar) developed for the Poker Flat Research Range in Alaska and Resolute Bay in Canada. MUIR consists of 16 “panels” with each panel acting as a separate radar. A panel includes 32 antenna element units (AEUs) in a fixed pattern, as well as a panel controller for communicating with and controlling the AEUs. It also contains an equal length RF feed network and a structure to support the components. The peak power is 512 kW, the aperture is 219.8 m^2, and the system temperature, which is used to define the system noise level, is 120 K. The phased array system allows us to change the radar beam direction every pulse transmission to any azimuth angle up to a maximum zenith angle of 25°. Widely used binary codes are available that enable MUIR to achieve high range resolutions and high frequency resolutions in the spectrum.

Figure 4 shows the external appearance of MUIR. On the red steel foundation, 16 panels are placed horizontally in a 4×4 configuration. (The wooden frame attached to the foundation is to prevent moose wandering under the radar where they could damage the cables.)

3 Observation results

This section looks at various HF-induced ionospheric irregularities measured with

Fig.4 *Photograph of MUIR*

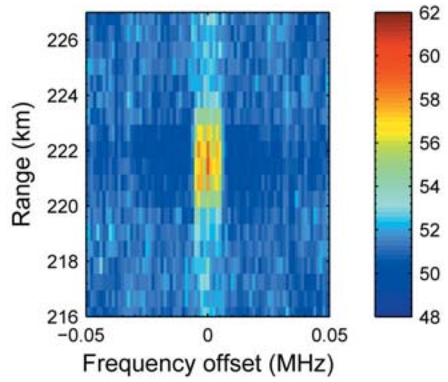

Fig.5a *An example of the color-coded HF-induced ion line measured with MUIR*

The x-axis shows the offset frequency from the radar frequency of 446 MHz. The y-axis shows the range in kilometers.

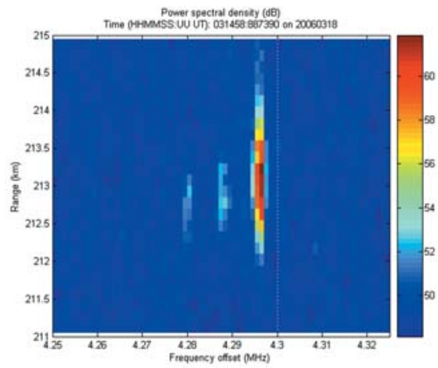

Fig.5b *The same as for Figure 5a except for the plasma line*

The vertical dotted line is plotted at the offset frequency shifted by the HF frequency of 4.3 MHz.

MUIR. In this paper, we discuss three examples taken from numerous results of experiments done over the past two years.

3.1 HF-induced ion line and plasma line

An example of the HF-induced ion line is shown in Fig. 5a. The x-axis is the offset frequency from the radar frequency of 446 MHz. The frequency width plotted here is ±50 kHz, although the receiver frequency width is much wider than what is shown. The y-axis is the range (not altitude) from the radar along the radar beam direction. Since the up B direction was selected for this experiment, the real height is a slightly smaller number than the range shown here. The range resolution is 600 m, because the baud length is 4 μs. Color contouring is used to show the signal-to-noise ratio (SNR) of the spectrum. Clear enhancements in the spectrum magnitude can be seen in the range from 220 to 223 km. While 2-s integration data was used to make this figure, the enhancement first appeared a few 100 ms after HF turn-on according to detail analyses using 10-ms data. The OTSI peak, which appeared at $\Delta f = 0$ MHz, can also be recognized as two ion acoustic peaks at $\Delta f = \pm 4$ kHz.

Figure 5b shows an example of the HF-induced up-shifted plasma line with f_{HF} of 4.3 MHz. The MUIR beam was directed to up B, and the range resolution was 150 m; that is, a 1-μs baud length. The figure format is the same as for Fig. 5a, except for the offset frequency. The strongest peak, which appeared at Δ4.296 MHz, is the decay line. The decay line can be seen within a 2-km range (about 1.9 km in altitude). The frequency difference from Δ4.3 MHz (about 4 kHz) corresponds to the ion acoustic frequency. Two cascade lines are seen at frequency displacements of twice and four times the ion acoustic frequency (about 8 and 16 kHz, respectively) from the decay line. In this case, there are two cascade lines, but the number of these lines is highly dependent on the ionospheric condition and the HF power. The first cascade line (8-kHz frequency shift from the decay line toward lower offset frequency) appeared in a narrower and lower altitude region than that for the decay line. This is because the Langmuir wave to generate the first cascade line is the daughter wave of the Langmuir wave that causes the decay line as shown in Fig. 1, and the daughter wave propagates along the magnetic field line.

3.2 Overshoot

Figure 6 shows temporal variations in the ion-line backscatter power with 10-ms time resolution. The time count starts when the HF-pump wave is turned on. In this case, the duration of the HF-pump wave is 1 s (as shown by vertical dotted lines). The ion-line intensity suddenly increases a few ten ms after HF turn-on. This phenomenon is called overshoot. The overshoot measured with the Arecibo IS radar starts within a few milliseconds, much sooner than in Fig. 6, because the Arecibo IS radar has higher sensitivity due to a larger aperture. The magnitude quickly decreases within 10 ms after the overshoot; in Fig. 6, the decrease is from about 105 to 100 dB. After this decrease, the magnitude gradually falls with time. Such temporal variations have been investigated regarding the generation/depression of ionospheric irregularities [Petviashvilli, 1976; Weatherall et al., 1982; Sheerin et al., 1982; Nicholson et al., 1984; Payne et al., 1984].

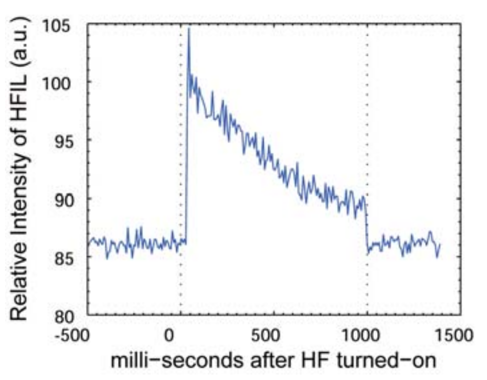

Fig.6 Temporal variations in the HF-induced ion line intensity

The x-axis shows the offset time in milliseconds after HF turn-on. The HF pump duration was 1 s as shown by the two vertical dotted lines.

3.3 Langmuir wave generation for the first 100 ms after HF turn-on

Figure 7 shows up-shifted plasma lines measured from three different radar-beam directions (geographical vertical, along the magnetic field line, and midway between the first two) at relative times of 33, 43, 103, and 113 ms after HF turn-on. The duty cycle of the HF pump wave was 100 ms on and 9.9 seconds off. The x-axis of each panel is the offset frequency from the radar frequency, and the y-axis on the left side is the altitude (the range for the individual directions is shown on the right). The number in the box in the upper-right corner of each cell is the MUIR beam angle; from top to bottom: vertical, middle, and up B, respectively. A MUIR coded-pulse of 998-μs length and 1-μs baud was transmitted every 10 ms while the beam direction was changed by the phased array system.

Spectra taken at 33 ms after HF turn-on are sensitive to the aspect angle, which is the angle difference between the radar beam direction and the local magnetic field line. The decay line and broad spectra appeared at the middle and up B directions, but there was no signal at the vertical. At 43 ms, four cascade lines more clearly appeared at up B, and the decay lines also appeared at the vertical. Of interest in the vertical spectrum is the double layer of the decay line. The decay line was much stronger at higher altitude than at lower altitude. While spectra from 53 to 93 ms are not shown here, those signatures were almost identical to spectra taken at 43 ms.

The last two spectra (at 103 and 113 ms) were taken after HF turn-off because the duration of the HF pump wave was 100 ms. Spectra at 103 ms, 3 ms after HF turn-off, still show clear decay and cascade lines for all directions. However, within 10 ms (at 113 ms or 13 ms after HF turn-off) all spectra were gone except for the up B; faint broad spectra can be seen at the offset frequency from 4.900 to 4.925 MHz.

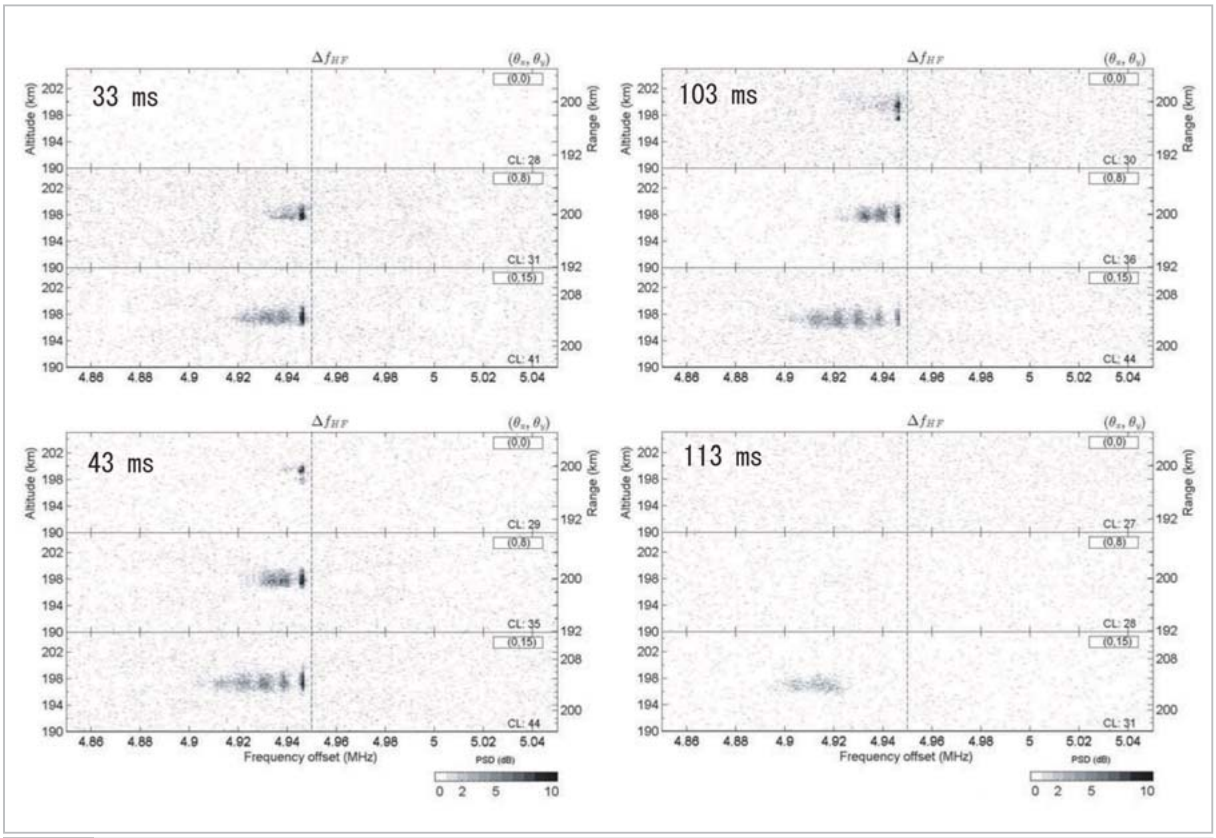

Fig.7 *Up-shifted plasma lines for the three MUIR beam directions (vertical, middle, and up B, from top to bottom of the panel)*

Four relative times (33, 43, 103, and 113 ms after HF turn-on) were selected to make these figures. The x-axis is the offset frequency from the radar frequency. The HF frequency used here was 4.95 MHz. The y-axis shows altitude, and the range for individual MUIR-beam directions is shown on the right.

This experiment provided the first results on the Langmuir-wave generation process for multiple directions.

4 Summary

This paper presents a portion of the observation results obtained from MUIR at HAARP during the artificial ionospheric modification experiments. The current HF peak power and available HF bandwidth of the HAARP facility make it a world leader in its capabilities. Various scientific projects are now being done at HAARP that involves collaboration between many instruments. MUIR is an important diagnostic tool, and it provides unique experimental information. Recent experiments on artificial ionospheric modification have tended to combine optical and radio wave instruments. Thus, some experiments at HAARP use various instruments located not only at HAARP but also at other sites such as the Poker Flat Research Range near Fairbanks.

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