Abstract

This paper presents experimental results derived from NOAA HF radar (dynasonde) measurements, acquired during the 1992 ionospheric modification campaign (Campaign'92) conducted at the UCLA HIPAS facility near Fairbanks, AK. During this campaign, the HIPAS transmitter was illuminating the ionosphere with high frequency electromagnetic waves at 2.85 and 4.53 MHz using a peak power of 1 MW, an antenna gain of 18.4 dBi, and a half power beamwidth of 22°. As a tool for ionospheric diagnostics, the dynasonde utilizes interferometry techniques to provide high-resolution echolocation, line-of-sight Doppler velocity, and digital ionograms as fundamental data products. Here we present results, which suggest that high-power, ordinary mode pump waves transmitted during "over-dense"
conditions can generate small-scale field-aligned irregularities and anomalous absorption, affecting diagnostic radio waves having both ordinary and extraordinary polarization. Furthermore, large-scale plasma density changes of ~30% were observed when the 2.85 MHz heater frequency matched that of the ionospheric critical plasma frequency.

Keywords: ionospheric modification, ionosonde.

1.0 Introduction

Since 1970 high-frequency (HF) electromagnetic (EM) waves radiated from high-power ground-based facilities have been used to modify the density and temperature of the ionospheric plasma. The first evidence of intentional ionospheric modification was obtained with an ionosonde operated at the Platteville (Colorado) high power transmitter facility. During these experiments, a variety of effects were observed in the ionosonde records [Utlaut et al., 1970; Utlaut and Violette, 1972; Utlaut and Violette, 1974]. In the latter work, Utlaut and Violette [1974] identified three major phenomena: (1) The production of artificial spread-F is observed at any time of day using heater frequencies ranging from at least 50% foF2 up to the critical frequency, with either O- or X-mode illumination. (2) When the heater is on for 10 minutes or more, a satellite trace is generated, paralleling the original pre-disturbed echo trace on the ionogram. With time, the satellite trace tends to move away from the original trace as heating continues and to move back after the heater is turned off, eventually merging with the original trace. (3) During times other than within about ±4 hours of local noon, anomalous wide-band attenuation has been observed, generally when O-mode illumination is used. It is well known that the generation of spread-F and anomalous absorption is strongly related to the small-scale field-aligned irregularities (FAI) excited by the processes of the parametric decay instability [Perkins et al., 1974] or the resonance
instability [Vaskov and Gurevich, 1977; Das and Fejer, 1979]. Graham and Fejer [1976] and Jones et al. [1984] have presented further theoretical work accounting for the anomalous absorption of EM waves due to scattering from FAIs into Langmuir waves.

Another effect observed with HF heating is the occurrence of large-scale plasma density perturbations. Using the HF heating facility at Tromsø (Norway), Jones et al. [1982] carried out the first detailed studies of large-scale heating in which the phase changes of the HF diagnostic signal provided information regarding the depletion of electron density in the ionosphere. Wright et al. [1988] used a dynasonde to measure changes in the critical frequency of the daytime Tromsø F-region during a heating experiment, also observing large-scale (15% in electron density) depletions. An overview of HF ionospheric modification research can be found in reviews by Fejer [1975, 1979], Duncan and Gordon [1982], Robinson [1989], Gordon and Duncan [1990], and Stubbe [1996].

The focus of this paper is the analysis of results obtained from a dynasonde deployed at Gilmore Creek, AK (64° 58' N, 147° 29' W) during the ionospheric modification campaigns carried out during September and October 1992 at the UCLA HIPAS Observatory. The results are mostly concerned with small-scale FAI, anomalous absorption of diagnostic waves, and large-scale plasma density changes, which occur when a high power HF radio wave illuminates the ionospheric F-region. The work of Wong et al. [1997] provides more detail relating to the ionospheric modification experiments already carried out at the HIPAS Observatory and describes much of the physics of the effects of high-power EM waves on the ionosphere.

2.0 Experimental Setup and Heating Methods

During Campaign'92, the ionospheric modification experiments were performed at the UCLA HIPAS Observatory, located ~45 km east Fairbanks, Alaska, at 64°52’ N, 146°50’ W.
The local magnetic field has a dip angle of 76°30′ and a declination of 28°02′; the magnetic field strength is approximately $5.1 \times 10^{-3}$ tesla at 250 km, giving a value of 1.43 MHz for the electron gyrofrequency. The HIPAS heater is comprised of eight crossed dipole antennas of which seven are equally spaced around a circle of radius ~104 meters while the eighth is located at the center; each antenna can be independently configured to transmit either O-mode or X-mode polarized waves. Details of the high-power radiating facility at the HIPAS Observatory are described in Wong et al. [1990]. During Campaign'92, the heater was illuminating the ionosphere using high-frequency electromagnetic waves at frequencies of 2.85 and 4.53 MHz with a peak power of 1 MW, an antenna gain of 18.4 dBi over a half power width of 22°. This yields a maximum effective radiated power (ERP) of 69 MW. We note that the 2.85 MHz pump frequency is close to the second harmonic of the local electron gyro-frequency. Recent experimental results reported by Ponomarenko et al. [1999] and Honary et al. [1999] have shown electron gyro-harmonic effects in HF coherent resonant scattering from EM waves that excited magnetic FAIs in the daytime ionospheric F-region plasma.

It is well known that upward propagating EM waves can couple to high-frequency electrostatic plasma waves and low-frequency ion-acoustic waves [Fejer, 1979]. During Campaign'92, the HIPAS Observatory utilized the three following techniques to indirectly generate low-frequency EM waves. In the first method, the high-frequency EM waves are amplitude-modulated at a frequency corresponding to the desired low frequency, e.g., an ion-cyclotron frequency of a particular ion species. The second method, termed the double-resonance method [Wong et al., 1979], utilizes two arrays of antennas, each at a different frequency and with a frequency separation equal to the desired low frequency. The excitation of a low frequency is a result of wave resonance and coupling. In the third method, the entire array is alternately set in-phase and out-of-phase so that the modified ionospheric region will
receive a focused beam during one half of a cycle and a diffuse beam during the other half. The net effect is an amplitude modulation at a low frequency. In this paper, the results of diagnostic ionograms recorded on Sep. 25 and Oct. 3, 1992, have been presented and discussed when the first and third heating methods were used.

3.0 Dynasonde Diagnostics and Results

A National Oceanic and Atmospheric Administration (NOAA) HF radar [Grubb, 1979], also referred to as a Dynasonde [Wright and Pitteway, 1979], was deployed at Gilmore Creek, AK, ~33 km north-west of the HIPAS Observatory where it was used to carry out high-precision spatial and temporal ionospheric measurements. The site was selected for diagnostic observations since it was at an appropriate distance from the HIPAS transmitter, such that the dynasonde receivers would not be saturated by the high power emissions, but yet close enough so as to effectively be underneath the modified ionosphere. At Gilmore Creek, the dynasonde used a delta antenna for transmitting and ionograms were acquired using the B-mode sounding pattern [Wright and Pitteway, 1979]. The ionospherically reflected echoes were received by two phase-matched receivers using a four-element multiplexed interferometer array which was structured in a L-shaped configuration with dipoles aligned in the north-south and east-west directions. Dynasonde measurements are derived from a set of four transmitted pulses at closely spaced frequencies, from which the time-of-flight and eight complex amplitude values are obtained by the two receivers. From these measurements, six phase parameters are derived, comprised of the corresponding phase of the reference point at the center of the crossed dipoles ($\Phi_{0}$), the phase differences due to antenna spacing in the east-west direction ($\Phi_{x}$), the north-south directions ($\Phi_{y}$), the phase changes due to time ($\Phi_{t}$), antenna orientation ($\Phi_{p}$), and a small sounding frequency increment ($\Phi_{f}$). These values are used to determine echolocation, Doppler shift, wave
polarization, as well as accurate virtual heights [Tsai et al., 1993, 1997; Wright and Pitteway, 1979].

3.1 Heating-induced small-scale FAIs

Figures 1a-e show five contiguous ionograms recorded from 0420 UT to 0445 UT (1820 to 1845 local time) on Oct. 3, 1992. During this time the HIPAS transmitter was continuously operational (0425 to 0445 UT) at a frequency of 2.85 MHz. In Figure 1, the O-mode diagnostic echoes are shown in green, and the X-mode echoes are shown in red. The first and second ionograms (Figures 1a and 1b) were recorded before and when the heater was just turned on, and remnants of spread-F are visible only where the diagnostic wave frequency is greater than 0.9 $f_{oF2}$ in O-mode or 0.9 $f_{xF2}$ in X-mode in both ionograms. After five and ten minutes of heating, respectively, Figures 1c and 1d show the same state for the original F traces for both the O- and X-mode echoes, i.e. echoes are still unspread when the diagnostic wave frequency is less than 0.9 of the critical frequency. Meanwhile, two satellite traces (O- and X-mode echoes) in which the spread-F occurs over the entire range of frequencies being reflected from the F-region are generated at virtual ranges ~40-80 km higher than the original traces. It has been found that E and F layers are not only smooth reflecting layers but also scatter radio energy from irregular structures and then occur spread features. From the review of spread F and ionospheric F-region irregularities by Herman [1966], there are two types of irregularities differentiated in the literature: large patches or referred to as large-scale irregularities, which have a horizontal extent up to several hundred kilometers, and individual small-scale field-aligned irregularities, whose sizes transverse to the magnetic field line are on the order of 1 km. Herman also mentioned that large patches are in actuality a collection of small-scale FAIs. In usual, ionograms show only one trace of ordinary echoes (excluding Z-mode traces and multi-hop traces) for E or F layer. These
concurrent satellite traces in Figures 1c and 1d and the accompanying spread-F echoes are evidences of the presence of local small-scale FAIs induced by the high-power HF EM waves.

After the heater is turned off, the satellite traces move back and eventually merge with the original traces, but the merged traces contained more spread F than the pre-heated ionograms, as shown in Figure 1e and subsequent ionograms. From these ionograms, we note that: (1) the heating-induced satellite traces were spread and occurred for both the O- and X-mode diagnostic echoes, (2) the heating-induced spread traces began from a frequency ~0.7 MHz lower than the pump frequency, but not \( f_{\text{min}} \), the lowest frequency at which ionospheric echo traces are observed on the ionogram, (3) the heating-induced spread traces have a greater virtual range distribution than the original traces, and (4) the critical frequencies of the spread satellite traces have the same value as the original traces. Observational point (1) suggests that the heating-induced FAIs scatter both O- and X-mode diagnostic echoes as usual ionospheric feature of spread-F. The points (2) and (3) illustrate that the FAIs are generated during heating in a region just below the reflection height of the pump and extend far beneath the very confined region (~10s of km in thickness), commonly referred to as the heated region. The thickness of the heated region can be roughly estimated by the difference of virtual ranges in the original trace at the pump frequency and the initial frequency of the heating-induced satellite trace. Furthermore, the cause of spread echoes and higher distribution can be explained as Klemperer’s interpretation [1963] for observations of spread F at high geomagnetic latitude in the following way. At high geomagnetic latitudes FAIs appear almost vertical to a radio wave incident from below. In the heated region, the electron density is less than the ambient, and then ducting or waveguide propagation occurs to give rise to the longer delay times (increased apparent ranges) observed on the induced satellite traces. In this example, it is difficult to estimate how much depletion of electron density occurred in the heated region. Other examples of large-scale electron density
perturbations and further discussion of observational points (3) and (4) will be presented in a later section when the pump frequency matched that of the ionospheric critical plasma frequency.

Additional information concerning the corresponding echolocation and echo amplitude of the diagnostic waves is presented in Figure 2. Utilizing fuzzy segmentation and connectedness techniques [Tsai and Berkey, 2000], we can classify the echoes appearing in these ionograms according to their reflection properties. In Figure 2, the upper panel represents the same ionogram as shown in Figure 1c but only shows the O-mode echoes; different segments within the ionogram are colored, distinguishing between the original trace (blue) and the heating-induced spread trace (brown). The segmented results are clearly classified for echoes that occur at frequencies less than 3.8 MHz, but both traces are merged together above 3.8 MHz and cannot be distinguished. The three middle panels represent spatial echolocations (skymaps) showing the projection of echoes onto a flat Earth and onto planes in the north-south and east-west directions. We note that all ionograms shown in this paper are virtual range (not virtual height) versus sounding frequency records. The virtual ranges are determined by one way time-of-flight multiplied by the light speed in free space, and the corresponding virtual heights are their z-axis projection values as shown in the center and right skymaps. The center skymap reveals that the echoes lie along the local magnetic field line, as the reflection surfaces are tilted southward. Furthermore, the heating-induced spread echoes (shown in brown) at frequencies less than 3.8 MHz are scattered from a more northward location, designated as the original reflection region (shown in blue) in the center skymap. It is concluded that the heating-induced irregularity areas were located to the north of the original reflection F-region even the heating transmitter (the HIPAS Observatory) is located ~33 km south-east of Gilmore Creek as described in the previous section. The small-scale irregularities can be theoretically explained by the mode conversion of EM waves into
Langmuir waves, which have much smaller group velocities than the EM waves. Consequently, Langmuir waves are much more efficiently absorbed by collisional damping than are the EM waves, and this leads to the growth of plasma density irregularities, which are highly elongated along the geomagnetic field. Anomalous absorption then arises when the powerful EM waves excite plasma instabilities in the diffusion-dominated ionospheric F-region.

3.2 Interpretation of the anomalous absorption of diagnostic waves

The lower panel in Figure 2 illustrates the amplitude distribution of the diagnostic signal and the result of averaging the amplitudes at frequency intervals of 0.2 MHz. The dots represent the echo amplitudes and the averages of those values are denoted by the solid lines for both the original F-region trace and the heating-induced spread-F. The mean amplitude difference is slightly less than 10 dB over the range of frequencies which are reflected from the F-region. For this reason the phenomenon was originally referred to as wide-band absorption due to scattering from the heating-induced FAIs. Utlaut and Violette [1974] also reported that anomalous absorption was visible on ionograms from slightly below the pump frequency up to the F-region critical plasma frequency although the heater frequency was close and within a few hundred kHz to the F-region critical frequency. In a review of ionospheric modification experiments at Tromsø, Stubbe [1996] stated that “anomalous absorption is found only if both the heating wave and the diagnostic wave are in the O-mode, and the frequency of the diagnostic wave should be within 500 kHz of the heater frequency.” However, Stubbe [1996] also mentioned that anomalous absorption rate increases with heater power usually. From earlier works of anomalous absorption observations at Tromsø also [Jones et al., 1984; Robinson, 1989], a series of ionospheric modification experiments showed that O-mode heating at 5.423 MHz and an ERP of 260 MW caused a considerable
diagnostic amplitude reduction at frequencies of 4.948, 5.701, 6.301, and 6.506 MHz (~1.1 MHz higher than the heater frequency), and the absorption phenomena was stronger for frequencies near the heater frequency than those further away. It is noted that the results of Figure 2 in this paper also show a little larger anomalous absorption (~9 dB) for the diagnostic frequency range from the pump frequency (2.85 MHz) to 3.4 MHz but less absorption in other frequency regions. Meanwhile, the results provide another evidence of wide-band absorption up to >1 MHz higher than the pump frequency at a heater power of 69 MW ERP.

Figures 3 and 4 show details of the heating modes as well as the temporal variation of ionospheric parameters derived from the ionograms, for two observing days (September 25 and October 3, 1992) during the ionospheric modification campaign. The temporal profiles of $f_{o}F_2$ and $f_{x}F_2$ are presented and referenced to conditions of under-dense or over-dense heating, depending on whether the pump frequencies of 2.85 MHz or 4.53 MHz are greater or less than the critical plasma frequency. The profiles of the maximum relative amplitudes of the ordinary and extraordinary mode echoes over the whole frequency range of the digital ionograms are also shown. We note that the maximum amplitudes of ordinary and extraordinary echoes are always obtained around the frequency at 0.8 of the corresponding critical frequency as shown as the original trace amplitude of Figure 2. As illustrated in Figures 3 and 4, during amplitude-modulated O-mode heating, the maximum relative amplitudes ($A_{o\text{max}}$) of the ordinary echoes are slightly decreased (~2-6 dB) relative to those of non-heating ionograms or the X-mode heating ionograms, suggesting increased ionospheric absorption. Meanwhile, the maximum relative amplitudes ($A_{x\text{max}}$) of extraordinary echoes tend to increase in those O-mode heating ionograms recorded from 0730 to 0740 UT and 0810 UT on Sept. 25 and from 0535 to 0540 UT on Oct. 3. One possible interpretation for this is that the diagnostic O-mode waves are reflected from a
northward region which is close to the heated F-region as indicated in Figure 2, whereas the X-mode waves are being reflected from an unperturbed (non-heated) region and therefore not affected by the heating transmissions. Another possible interpretation is that D-region absorption can be enhanced during O-mode heating [Stubbe, 1996]; the diagnostic O-mode waves are propagating through the heated D-region, whereas the X-mode waves are propagating through an unperturbed (non-heated) D-region. However, the enhanced D-region absorption cannot be applied to be the cause of wide-band absorption of the heating-induced satellite trace observed in Figure 2 because the ~9dB amplitude decrease is the difference of the mean amplitudes for the original trace and the satellite trace. Such D-region absorption should occur to both of the original and satellite traces and therefore not affect the amplitude difference.

Furthermore, in Figures 3 and 4, the filled circles for the \( f_{oF2} \) profiles denote that heating-induced spread satellite traces appeared in the ionograms recorded from 0809 to 0820 UT on Sept. 25 and from 0435 to 0440 UT, 0536 to 0545 UT, and 0557 to 0600 UT on Oct. 3. We note that most of the heating-induced FAIs occurred during periods of amplitude-modulated and ordinary polarization mode heating, under the condition of over-dense heating, i.e. when the heater wave frequency was less than the F-region critical frequency. The observed FAI results are consistent with results outlined in the review by Robinson [1989] for a number of modification experiments carried out at Tromsø.

### 3.3 Large-scale Plasma Density Perturbations

As described in the previous section, FAIs can be induced by a high power EM wave of ordinary polarization under over-dense heating conditions, causing spread satellite traces on the diagnostic ionograms for both O- and X-mode echoes. We further pointed out that the heated region lies below the reflection height of the pump waves. Moreover, as shown in the
ionograms of Figures 1 and 2, when powerful EM waves are radiated during the condition of over-dense heating, when the pump frequency (2.85 MHz) is much less than the F-region maximum plasma frequency, the recorded ionogram shows a higher virtual range distribution for the heating-induced spread trace than the original trace, even though the corresponding critical frequency of the heating-induced spread trace has the same value (~4.1 MHz) as the original trace. It appears that the pump waves can deplete the electron density within the heated region of the ionosphere, where higher virtual range distributed spread traces are generated. However, the powerful EM waves do not affect the ionosphere above the reflection height for the pump waves, so the critical frequency of the heating-induced spread traces remains the same as the original traces during over-dense heating conditions.

Further evidences for large-scale plasma density depletions by high power EM waves is presented in Figures 5 for the condition when the heater frequency (2.85 MHz) matches the plasma frequency at $f_{oF2}$. Figures 5a and 5c show two ionograms recorded at 0632 UT on Sept. 25 and at 0455 UT on Oct. 3, respectively, but no heating-induced spread traces. (The upper spread traces in Figure 5a are generated by second-hop echoes.) Figures 5b and 5d show another two ionograms with heating-induced traces recorded at 0809 UT on Sept. 25 and at 0539 UT on Oct. 3 when the critical plasma frequency approaches the heater frequency of 2.85 MHz. As in previous examples, these ionograms show O-mode diagnostic echoes in green and X-mode echoes in red. An estimate of electron density depletion can be approached by measuring the critical frequencies of both the original trace and the heating-induced trace. Two manually plotting lines in Figures 5b and 5d present the virtual height versus plasma frequency information of the original trace (the lower line) and the heating-induced satellite trace (the upper line). The results show that, as presented in Figures 5b and 5d, the heating-induced traces are still spread due to scattering from FAIs as discussed in Section 3.1; furthermore, nearly the same critical frequency (~2.4 MHz) of the heating-
induced traces was obtained on ionograms recorded on two different days when the pump frequency matched the ionospheric critical plasma frequency. It is well known that the electron density in the ionosphere is proportional to the square of plasma frequency. This shows that a depletion of ~30% was induced for the condition of amplitude-modulated O-mode heating and the heater frequency of 2.85 MHz matching the plasma critical frequency.

4.0 Conclusions and Summary

In this paper, we have focused on three related phenomena, which occur when high-power EM waves in the HF range interact with the ionospheric F-region. These are (1) small-scale field-aligned irregularities (FAIs), (2) the anomalous absorption of low power diagnostic waves, and (3) large-scale plasma density depletions. From diagnostic observations carried out using the dynasonde during the HIPAS 1992 ionospheric modification campaigns, we observed highly spread satellite traces of relatively weaker amplitude in both O- and X-mode echoes when the transmitted pump waves were polarized in O-mode and during the condition of over-dense heating. We conclude that such powerful EM waves are efficient in inducing the generation of small-scale FAIs and causing anomalous absorption of the diagnostic waves. Further evidence suggests that the heated region lies northward of the original diagnostic echolocation and below the reflection height of the pump waves. Furthermore, when the heater frequency matches the critical frequency of the F-region, high-power EM waves having O-mode polarization can cause depletions of ~30% in ionospheric plasma density for a pump frequency of 2.85 MHz.

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References


Jones, T. B., T. Robinson, H. Kopka, and P. Stubbe, 1982, Phase changes induced in a
diagnostic radio wave passing through a heated region of the auroral ionosphere, J.
Jones, T. B., T. Robinson, P. Stubbe, and H. Kopka, 1984, Frequency dependence of
anomalous absorption caused by high power radio waves, J. Atmos. Terr. Phys., 46, 147-
153.
Klemperer, W. K., 1963, Characteristics of spread F at high geomagnetic latitude, J. Geophys.
Res., 68, 3191-3196.
Perkins, F. W., C. Oberman, and E. J. Valeo, 1974, Parametric instabilities and ionospheric
Ponomarenko, P. V., T. B. Leyser, and B. Thidé, 1999, New electron gyroharmonic effects in
HF scatter from pump-excited magnetic field-aligned ionospheric irregularities, J.
Robinson, T. R., 1989, The heating of the high latitude ionosphere by high power radio
Phys., 58, 349-368.
Tsai, L.-C., F. T. Berkey, and G. S. Stiles, 1993, On the derivation of an improved parameter
Tsai, L.-C., F. T. Berkey, and G. S. Stiles, 1997, derivation and error analysis of echo phase
Tsai, L.-C., and F. T. Berkey, 2000, Ionogram analysis using fuzzy segmentation and
connectedness techniques, accepted by Radio Sci.


Figure 1. Five contiguous ionograms on October 3, 1992, illustrating spread-F and satellite traces appearance and disappearance with HIPAS heating at a pump frequency of 2.85 MHz.
The ordinary and extraordinary echoes are shown in green and red, respectively. During this time the HIPAS transmitter was continuously operational from 0425 to 0445 UT.
Figure 2. The upper panel shows the same ionogram of Figure 1c but ordinary mode polarization echoes only with different characterized segments in color. The three middle graphs show corresponding echolocation in different views of skymaps onto a flat Earth (the left skymap), a plane in the north-south direction and virtual height (the center skymap), and a plane in the east-west direction and virtual height (the right skymap). The lower panel presents echo amplitude and their mean values in dot points and linked lines.
Figure 3. $foF2$, $fxF2$, and maximum relative amplitude temporal profiles for both of ordinary and extraordinary echoes recorded on September 25, 1992, with HIPAS heating. The filled circles in $foF2$ profiles mean that heating-induced spread satellite traces occurred in the recorded ionogram. $A_{omax}$ and $A_{xmax}$ are the maximum relative amplitudes for ordinary and extraordinary echoes, respectively, over the whole frequency range of the ionograms.
Figure 4. $foF2$, $fxF2$, and maximum relative amplitude temporal profiles for both of ordinary and extraordinary echoes recorded on October 3, 1992, with HIPAS heating. The filled circles in $foF2$ profiles mean that heating-induced spread satellite traces occurred in the recorded ionogram. $A_{omax}$ and $A_{xmax}$ are the maximum relative amplitudes for ordinary and extraordinary echoes, respectively, over the whole frequency range of the ionograms. Meanwhile, the heating method during 5:45 to 6:30 UT is 3 minute continue wave transmitting at the pump frequency (no modulation) and then 3 minute pulse transmitting with 30 µsec pulse width and 30 Hz repeat rate.
Figure 5. Examples to show ionograms without (5a and 5c) and with (5b and 5d) large-scale plasma depletion during heating. The ordinary and extraordinary echoes are shown in green and red, respectively. Two manually plotting lines in 5(b) and 5(d) present the virtual height versus plasma frequency information of the original trace (the lower line) and the heating-induced satellite trace (the upper line).