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FINAL TECHNICAL REPORT
AUGUST 1971

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PHOTOMETRIC STUDIES OF MODIFIED IONOSPHERIC BEHAVIOR

PART B

UNIVERSITY OF PITTSBURGH

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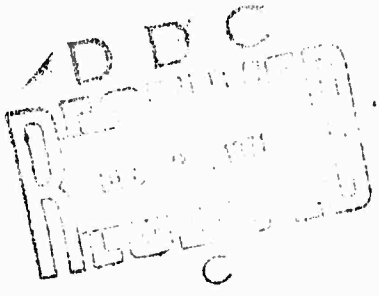

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Photometric Studies of Modified Ionospheric Behavior

FINAL REPORT "B" 27 Oct 69 to 30 Jun 71

M.A. Biondi
R.D. Hake
D.P. Sipler

August 1971	28	4

F30602-70-C-0099 ARPA Order 1423	RADC-TR-71-222, Part B

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This final report describes the method developed for detecting radio frequency heating of the electrons in the F region through attendant effects on the intensity of radiation from excited oxygen atoms in that region of the ionosphere. The changes in the F region of the ionosphere produced by r.f. energy from a powerful (1.6 Mw) ground-based transmitter at Platteville, Colorado, were detected optically by a spatial-scanning filter photometer constructed for the purpose. At low electron temperatures and small r.f. heating, the intensity of the atomic oxyges ($^1D \rightarrow {}^3P$) 6300A radiation is decreased (suppressed) as a result of reduced electron-ion recombination production of excited oxygen atoms in the ^1D state. At higher electron temperatures and/or stronger r.f. heating, the 6300A intensity is increased (enhanced) as a result of electron impact excitation of ground state (^3P) oxygen atoms to the excited (^1D) state.

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Ionospheric Heating

Photometry

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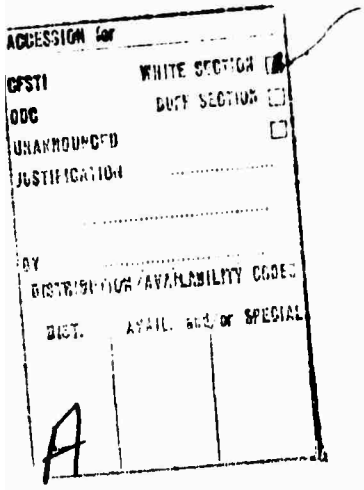

PHOTOMETRIC STUDIES OF MODIFIED IONOSPHERIC BEHAVIOR

Part B

M. A. Biondi
R. D. Hake, Jr.
D. P. Sipler

Contractor: University of Pittsburgh
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PUBLICATION REVIEW

This technical report has been reviewed and is approved.

RADC Project Engineer

RADC Contract Engineer

FINAL REPORT B

"Photometric Studies of Modified Ionospheric Behavior"

by

M. A. Biondi, R. D. Hake, Jr. and D. P. Sipler

Contract No. F30602-70-C-0099

Rome Air Development Center

Griffiss Air Force Base

New York 13440

27 October 1969 to 30 June 1971

Sponsored By
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Technical Report Summary

This final report describes the method developed for detecting radio frequency heating of the electrons in the F region through attendant effects on the intensity of radiation from excited oxygen atoms in that region of the ionosphere. At low electron temperatures and small rf heating, the intensity of the atomic oxygen ($^1D \rightarrow {}^3P$) 6300A radiation is decreased ("suppressed") as a result of reduced electron-ion recombination production of excited oxygen atoms in the ^1D state. At higher electron temperatures and/or stronger r-f heating, the 6300A intensity is increased ("enhanced") as a result of electron impact excitation of ground state (^3P) oxygen atoms to the excited (^1D) state.

The increase in electron temperature in the F region of the ionosphere produced by absorption of rf energy from a powerful (1.6 Mw) ground-based transmitter at Platteville, Colo. was detected optically by a spatial-scanning filter photometer constructed for the purpose. Our predicted intensity suppression signals in the atomic oxygen 6300A radiation from the nighttime ionosphere were observed on a number of occasions in May 1970. The magnitude of the suppression signal indicates that a 30% increase in electron temperature was produced by the transmitter when X-mode wave propagation was used. In Sept. and Oct. 1970, when O-mode propagation was used, strong 6300A intensity enhancement signals were observed. These signals correspond to significant production of energetic (> 2 eV) electrons. A likely source of these energetic electrons is plasma instabilities excited in the F region of the ionosphere when the rf electric fields associated with O-mode propagation exceed a critical level. (The critical level required for X-mode propagation is shown to be substantially larger; therefore excitation of plasma instabilities is not expected in the latter case.)

"Photometric Studies of Modified Ionospheric Behavior"

M. A. Biondi, R. D. Hake, Jr. and D. P. Sipler

University of Pittsburgh

This research was supported by the
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M. A. Biondi
Principal Investigator

1. Optical Observations of the Boulder Ionospheric Modification Experiment

A. λ6300 Optical Signals

The elevation of electron temperature in the F region in response to radio frequency energy from a powerful ground-based transmitter is expected to produce observable effects on the nightglow λ6300 atomic oxygen emission from that region. Under quiescent conditions, the nightglow λ6300 ($^1D - {}^3P$) radiation is produced by dissociative recombination of O_2^+ ions with electrons,

$$O_2^+ + e \xrightarrow{\alpha} O^* + O'^* \quad , \qquad (1)$$

where one or both of the product atoms may be in the ^1D excited state. Since the recombination coefficient α varies as $T_e^{-0.6}$ (T_e is the electron temperature), an increase in electron temperature leads to a decrease in the rate of production of $O(^1D)$ excited atoms and consequently a transient decrease in the intensity of λ6300 radiation[1, 2]. (The λ6300 intensity returns to the original quasi-stationary value determined by the rate of production of O_2^+ by charge transfer from O^+.) Alternatively, if the electron temperature is raised sufficiently, direct electron impact excitation of the ambient atomic oxygen,

$$e_{fast} + O(^3P) \rightarrow e_{slow} + O^*(^1D) \quad , \qquad (2)$$

leads to an increased rate of production of ^1D and hence of λ6300 intensity[3]. This enhancement is a continuing process and leads to a new quasi-stationary value of λ6300 intensity.

Calculations of the expected magnitudes of the λ6300 intensity modulations indicate that for a base $T_e \leq 1500°K$, where reaction (1) predominates, a ~ 20% increase in T_e can be detected as an intensity suppression signal, while for $T_e \gtrsim 1500°K$ a 30% increase in T_e produces

a measurable intensity enhancement signal via reaction (2). Accordingly, a spatial scanning filter photometer was constructed to detect electron heating in the F region through the attendant effect on the λ6300 [and possibly the λ5577 ($^1S \rightarrow {}^1D$)] nightglow radiation. The instrument was deployed in 1970 at Erie site some 26 km west of the Platteville 1.6 Mw transmitter designed and constructed by the group under the direction of W. F. Utlaut of the Institute for Telecommunication Sciences, U. S. Dept. Commerce.

B. Photometer Apparatus

1. General

The instrument constructed for this work is a two channel, spatial scanning photometer with an automatic control and data recording system. Two identical photometers are used for simultaneous observation at two wavelengths. A mirror, driven in two axes, is used to effect a spatial scan. Pulses from the phototube are counted and recorded on 1/2 inch computer-compatible digital magnetic tape.

2. Photometers

Each of the photometers consists of an interference filter, lens, and photomultiplier detector with an aperture to define the field of view. Four interference filters are provided, two for each photometer. One photometer can use either a 6300A or a 5552A filter, while the other photometer can use either a 6333A or a 5577A filter. This permits observation of the red and green lines simultaneously, or one of the lines and a nearby wavelength region to be used as a background intensity monitor region. Center wavelengths and passbands of these filters are given in Table I with other essential characteristics.

Table I

Filter	Center Wavelength	FWHM	Transmission at line (%)
5552A	5552.5A	12.2A	------
5577A	5577.5A	12.2A	61
6300A	6300.0A	10.7A	66
6334A	6334.3A	10.4A	------

The lens is a 2 inch diameter 5 inch focal length achromat. Light coming through the lens is focused on the photocathode of an EMI 9558A phototube. The 9558A tube is selected for low dark current and high red sensitivity. A 1/2 inch aperture is placed just before the photocathode, defining the field of view of the photometer. In order to eliminate the electrons from the area of the 2 inch photocathode outside the aperture, a cylindrical magnetic lens was placed on front of the photocathode. The diverging magnetic field carries electrons from the edge of the photocathode to the walls of the tube, avoiding the multiplying surfaces. Thus the electrons in the center are the only electrons to be multiplied and counted. The photomultiplier tube, aperture, and magnet are contained in a PFR model TE102TS thermoelectric cooler. These coolers reach a temperature of about - 15°C, which is close to the optimum temperature for the phototubes (- 20°C).

3. Scanning Mirror

The scanning mirror arrangement is held on a frame which is movable about an axis in the plane of the mirror (Y axis). The mirror frame is mounted on ball bearings on a secondary frame which is movable about the X axis (perpendicular to the Y axis and on the axis of the photometers). A stepping motor is used to drive each axis. The stepping motor for the Y axis is placed as close as possible to the X axis in order

to minimize the moment of inertia about the X axis.

The entire photometer and mirror system is mounted on a surplus radar mount, so that it can be aimed at any point in the sky. The original servo driving motors are run on a reduced DC voltage to slow the response of the system to a point where it can be run to a desired orientation by manually operated switches without large accelerations which might damage or misalign the system.

4. Data Recording System

The photomultiplier pulses are amplified and differentiated, fed into a fast voltage comparator and pulse shaping circuit, and then into an 18 bit counter. A 100 Khz signal from a crystal oscillator is divided by a series of counters down to 2Hz, 1Hz, and 0.5Hz pulse trains. One of these pulse trains is selected by a switch and used to define the data rate of the digital system. This data rate pulse (DR pulse) stops the 18 bit counters while the data are gated into storage registers. The counters are cleared to zero and started again. Data from the storage registers go to D/A converters, and then to a Brush model 220 chart recorder.

The DR pulse also gates the data into 6 shift registers, each 12 bits long. The arrangement of the data in these registers is shown in Table II. These data are shifted from the registers into a Kennedy model 1600H incremental tape recorder. In addition to the two 18 bit counter words, time, filter information, scanning mirror position and an identification number are placed on the tape (see Table II).

5. Scan Programming

In the stepping motor control section, switches are provided to generate four numbers, $n_1 \ldots n_4$, which determine the scan sequence. The DR pulse starts a pulse train of n_1 pulses into the Y axis stepping motor driver, driving the stepping motor in one direction. This is

Table II

Information on Tape	No. of bits
Output of counter 1	18
Output of counter 2	18
X axis position	5
Y axis position	5
Time	12
Identification	6
HEAT Signal	1
Filter in use (Ch. 1)	2
Filter in use (Ch. 2)	2

repeated for $(n_2 - 1)$ DR pulses. On the n_2th DR pulse, $n_1(n_2 - 1) + 1$ pulses are sent to the Y axis stepping motor driver, driving the motor the other way, returning to a position 1 step past its original position. This insures that the original position of the stepping motor is right on the lower limit switch at the start of every scan. At the same time, n_3 pulses are sent to the X axis stepping motor driver. The above process is repeated until the $2n_2$th DR pulse, when n_3 more pulses are sent to the X axis driver. This is repeated until the n_2 n_4th DR pulse, at which time $n_3(n_4 - 1) + 1$ pulses are sent to the X axis driver and $n_1(n_2 - 1) + 1$ pulses are sent to the Y axis driver, sending both stepping motors back to the position they held at the start of the spatial scan (i.e. against the lower limit switches).

The above process results in a n_2 x n_4 position scan of the sky by the scanning mirror. n_2 and n_4 are independently adjustable between 2 and 7, and n_1 and n_3 are independently adjustable between 6 and 30. A

[illegible] scan was normally used in the operation at Boulder, with 10-30 steps/position. Pulses were sent to the stepping motors at a rate of about 90-120 Hz. Faster rates were attempted, but the stepping motors had trouble starting and would miss steps. Since the construction of the stepping motor causes it to miss steps in multiples of 4, the angular error introduced is unacceptable. Since as many as 30 stepping pulses can be used, the time that the mirror is in motion may be as long as 1/3 sec for a position change, and n_2 or n_4 times that for the return. Since this is an appreciable part of 1 sec, the actual scanned pattern will be "smeared" to this extent. For this reason, a data rate of 0.5 Hz was used for most spatial scans, to minimize this smearing.

A 12 bit clock was provided which counted the 2 Hz pulses from the timing clock. Both clocks were reset to zero at the change of state of the HEAT (rf heating) signal. The 12 time bits, therefore, measure the elapsed time from the change of state of the HEAT signal from 1 to 0 or 0 to 1. This was originally designed to allow completely automatic operation, using a signal from the heating transmitter as the HEAT signal. This turned out to be impracticable, however, and the HEAT signal is now manually generated by a front panel switch. The HEAT change of state also resets the scanning mirror and places an end of record gap on the digital tape.

C. Observations

The dual channel filter photometer was fielded at Erie, Colorado site and operated from March 1970 to December 1970, at which time it was shipped to Arecibo for observations of similar ionospheric modification attempts. Although optimum optical "seeing" conditions occurred somewhat infrequently, and problems with rf transmitter limited the number of nights of operation, [illegible]

turning on and off of the 1.6 Mw transmitter were detected on some twelve different nights. Both intensity suppression (electron-ion recombination) and intensity enhancement (electron impact excitation) λ6300 signals were observed at different times and for different rf propagation modes.

In the presence of the earth's magnetic field the ionosphere acts as a magnetoplasma and so supports two normal modes of propagation, the ordinary polarization (O-mode) wave and the extraordinary polarization (X-mode) wave. For both modes of propagation maximum absorption of the rf energy occurs at the point at which the index of refraction of the plasma is a minimum. For the O-mode this occurs where the local plasma frequency ω_p equals the rf transmitter angular frequency, ω. For the X-mode, this occurs at a slightly lower value of ω_p, depending on the strength of the dc magnetic field in the plasma. Since ω_p depends on the local electron density n_e according to the relation,

$$\omega_p = \sqrt{4\pi\, n_e\, e^2/m} \quad , \qquad (3)$$

maximum heating takes place at that particular height in the ionosphere where the appropriate electron density is found. Thus, except for spreading of the energy by heat conduction in the electron gas, the enhancement in electron temperature should be rather localized, with an attendant localization of the λ6300 intensity signal.

The first detected modification of λ6300 intensity was produced with the transmitting antenna propagating the extraordinary polarization. On 13 May and 15 May 1970, as the electrons in the F region were heated by turning on the transmitter, the λ6300 intensity was seen to decrease and then recover, as predicted by the theory based on electron-ion recombination production of the $O(^1D)$ radiating atoms[1, 2]. After the transmitter had been on for some time, so that the electrons had reached

a steady elevated temperature, the turning off of the transmitter produced the predicted momentary increase and recovery in λ6300 intensity. The data for 15 May 1970, with the normal slow decay in λ6300 nightglow intensity removed, are shown as a graph of intensity modulation versus time in Fig. 1. Although statistical fluctuations in the data (see $\pm \sqrt{N}$ on the graph) mask the detailed shapes of the intensity modulations, an abrupt decrease in intensity with the turning on of the transmitter and an abrupt increase with turning off are apparent. The dashed lines represent the theoretical predictions of the effect using known values of the recombination coefficient and reasonable estimates of n_e, T_e and $O(^1D)$ lifetime. The excursions noted are consistent with a change in electron temperature $\Delta T_e/T_e \simeq 35\%$.

Although intensity suppression signals of the type shown in Fig. 16 were observed when extraordinary polarization was used, a much larger modulation, of the opposite sign (intensity enhancement), was produced when ordinary polarization waves were propagated. These signals are of the type expected when excitation of $O(^1D)$ by impact of energetic (> 2 eV) electrons adds to the usual recombination production of $O(^1D)$ in the nightglow. A particularly good example of the enhancement signals observed is given in Fig. 2, which shows the absolute intensity of λ6300 as a function of time on the night of 25 September 1970. (The time corresponding to t = 0 on the graph is 2030 MDT.)

The first transmitter turn on required some time to reach full power; therefore the intensity enhancement at first builds rather slowly. Initial intensity enhancements of ~ 20 Rayleighs were observed when the transmitter frequency f was appreciably less than the plasma or critical frequency at the F_2 peak ($f_o F_2$). However, as the ionospheric electron density decayed, $f_o F_2 \rightarrow f$ and the intensity enhancement increased to ~ 30 Rayleighs just before $f_o F_2$ decreased below f. If, under the action of

the rf heating wave, the electrons maintain a near-Maxwellian energy distribution, the observed enhancements require a final electron temperature in excess of 2000°K. The significance of this observation is discussed in the next subsection.

Since the intensity enhancement is a sensitive indicator of the region where the most energetic electrons are, the spatial scans are of interest for comparing the observed location of maximum heating with that predicted by ray tracing. The data for O-mode propagation on the night of 30 October 1970 are shown in Fig. 3. The center spot (No. 5) in the photometer's 3 x 3 scan pattern was aimed approximately at the point in the ionosphere where ray-tracing for a model ionosphere suggested maximum energy absorption should occur. The numbers in the circles on the left half of the figure are λ6300 intensity enhancements for each of the 9 scan positions. The same data are shown as intensity enhancements versus position in the right half of Fig. 3. Maximum enhancement apparently occurred a few degrees east and south of the center spot in the scan pattern. No calculations of ray-bending are carried out for the particular ionospheric electron distribution of a given night; thus this agreement between observed and predicted (for a "typical" ionosphere) heating location is considered to be quite satisfactory.

Later the same night, a test of intensity enhancement as a function of transmitter power was attempted. Observations are only shown for two power levels, since the transmitter failed shortly after the third turn-on. The λ6300 intensity (corrected for background) is shown in the lower part of Fig. 4. It will be seen that the 40 Rayleigh enhancement produced at 1.6 Mw power from the transmitter is appreciably reduced (to 33 Rayleighs) when the power level is reduced to 1.5 Mw three minutes later. Thus the number of electrons attaining kinetic energies greater than 2 eV is a

sensitive function of the rf power level. More detailed analysis of this dependence of F region electron energy on rf power density awaits correlation of our data with other observations (e.g. ionosonde records).

In addition to the use of the optical enhancement signals to determine the extent of F-region electron heating, the measurements of the λ6300 intensity transients provide a means of in-situ determinations of the lifetime of the $O(^1D)$ atoms, which is often considerably shorter than the 110 sec. radiative lifetime as a result of quenching of the excited state on collisions with ambient N_2 and O_2 molecules. Since the λ6300 radiating region is reasonably localized in altitude at any instant and this altitude changes with time as the heated level rises (at constant transmitter frequency and decaying nightime electron density), one can obtain $O(^1D)$ lifetimes as a function of altitude from a series of intensity enhancement transients.

As an example, the differences between the stationary state values and the measured intensities are plotted for the first transmitter turn on and first turn off in Fig. 5. It will be seen that the slopes of the semi-logarithmic plots give lifetimes of (13.1 ± 1) and (12.7 ± 0.5) sec, both of which indicate heating at a rather low altitude (≤ 240 km) in the early evening when $f_o F_2$ was substantially greater than the transmitter frequency*. Here again, quantitative evaluations await correlation of our data with ionosonde records of electron density vs. height for the times of interest. Such correlations will be made at the Summer 1971 workshop on the ionospheric modification experiments.

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*Preliminary examinations of ionosonde records indicate that the height at which $\omega_p = \omega$ was ~ 220 km some 30 min. after this measurement. Thus the measured $O(^1D)$ lifetimes are consistent with intensity enhancements originating from this level of the ionosphere.

D. Discussion

The dual channel filter photometer fulfilled its function in detecting λ6300 intensity modifications resulting from F region electron energy changes induced by the turning on and off of the Platteville 1.6 Mw transmitter. The first intensity modulations so induced were feeble suppression signals (~ 5% in amplitude, c.f. Fig. 1); however in later experiments the intensity enhancements of ~ 40% were easily detected (c.f. Fig. 2). At first it was not clear whether the change from the "modest" intensity suppression signals (electron-ion recombination) to the more striking intensity enhancement signals (electron impact excitation) was the result of the change from X-mode to O-mode signal propagation from the transmitter or was due to an elevation in base electron temperature. This elevation in base T_e is expected to occur when the point in the southern hemisphere magnetically conjugate to Platteville is in sunlight and bombards the nighttime F-region over Platteville with energetic photo-electrons which have been guided along the earth's magnetic field lines.

The answer to this question appears to be given by the data summarized in Table III. It will be seen that, although the conjugate point was sunlit during the observing period on 25 and 30 Sept. and on 30 Oct.,

Table III

Observation Date	Propagation Mode	Sunlit Conjugate Point	λ6300 Signal
13 May 1970	X	No	Suppression
15 May 1970	X	No	Suppression
25 Sept. 1970	O	Yes	Enhancement
30 Sept. 1970	X	Yes	Suppression
30 Oct. 1970	O	Yes	Enhancement

the signal changed from strong enhancement (high electron energies) to suppression (low electron energies) when the propagation mode was switched from O to X. The observation of intensity suppression signals during sunlit conjugate is evidence that the base T_e on both 25 and 30 Sept. was substantially less than 1500°K.

If the O-mode electron heating were the result of ordinary collisional absorption, then the enhancements on 25 Sept. would require a final T_e in excess of 2000°K, which represents an unusually large $\Delta T_e/T_e$ (approaching 100%) in comparison to the predicted (~ 30%) values. An alternative explanation for the large intensity enhancements is to be found in the suggestion that the O-mode wave excites some form of parametric instability in the plasma. In this case electron acceleration by the electric field of a plasma wave can lead to production of energetic electrons, and a non-thermal high energy tail may be generated in the electron energy distribution. This high energy tail can lead to the observed, large intensity enhancements without requiring that the <u>average</u> energy of the electrons in the ionosphere be unduly increased by the absorption of rf energy.

The reason that O-mode propagation leads to generation of a plasma instability, while the X-mode propagation does not, is probably the following. Nishikawa[4] has suggested that the parametric instability is triggered whenever the electric field of the heating wave exceeds a threshold value [which varies approximately as $(\omega-\omega_p)^{3/2}$] and the transmitter frequency has the value $\omega = \omega_p \pm \omega_{ia}$, where ω_{ia} is the ion acoustic wave frequency and $\omega_{ia} \ll \omega_p$. Now the O-mode wave is reflected at the point in the ionosphere where $\omega = \omega_p$, while the X-mode is reflected at a lower altitude, where $\omega \simeq \omega_p + \omega_H$ (ω_H is the electron cyclotron frequency). Thus only a small fraction of the X-mode wave's energy penetrates to the region where the plasma instability is readily excited, leading to a much higher

threshold power for X-mode excitation of the plasma instability than for O-mode.

In view of the interest in the question of excitation of plasma instabilities, in future studies we propose to investigate the matter further by searching for an effect on the λ5577 [$O(^1S) \rightarrow O(^1D)$] intensity at the same points in the ionosphere where we find the λ6300 enhancements. It appears to us that production of energetic electrons by the plasma instability may lead to detectable impact excitation of the oxygen atoms from their ^3P ground state directly to the ^1S excited state (threshold energy ~ 4 eV). In order to detect this enhancement in the λ5577 intensity in the presence of the rather large natural fluctuations in nightglow λ5577 intensity, it will be necessary to run the transmitter on short on/off cycles (~ 20 - 40 seconds) and use our photometer in its coherent summing mode for many cycles to average out the natural intensity fluctuations and thus detect any weak enhancements.

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Figure Captions

(1) Intensity suppression signal associated with rf heating produced by X-mode propagation on 15 May 1970. The normal, slow decay of λ6300 intensity has been subtracted from the data. The dashed curves are fits of the theoretical model based on dissociative recombination production of $O(^1D)$ - see text for details.

(2) Intensity enhancement of λ6300 produced by O-mode propagation on 25 Sept. 1970. Such enhancements are associated with electron impact excitation of $O(^3P)$ atoms to the excited (^1D) state.

(3) Spatial scan showing localization of the λ6300 intensity enhancement produced by O-mode propagation on 30 Oct. 1970. The circles represent the 6° detection cones of the photometer which are separated by approximately 8° in the various scan locations. The central spot of the scan (No. 5) was aimed at the expected center of the heated region. The numbers in the circles are the enhancements (in counts).

(4) λ6300 intensity enhancement as a function of rf transmitter power. During the third turn-on the transmitter failed.

(5) Effective lifetimes of the $O(^1D)$ excited atoms determined from the λ6300 intensity transients produced during the first turn-on and first turn off of the transmitter shown in Fig. 4. (See text for the details of the analysis.)

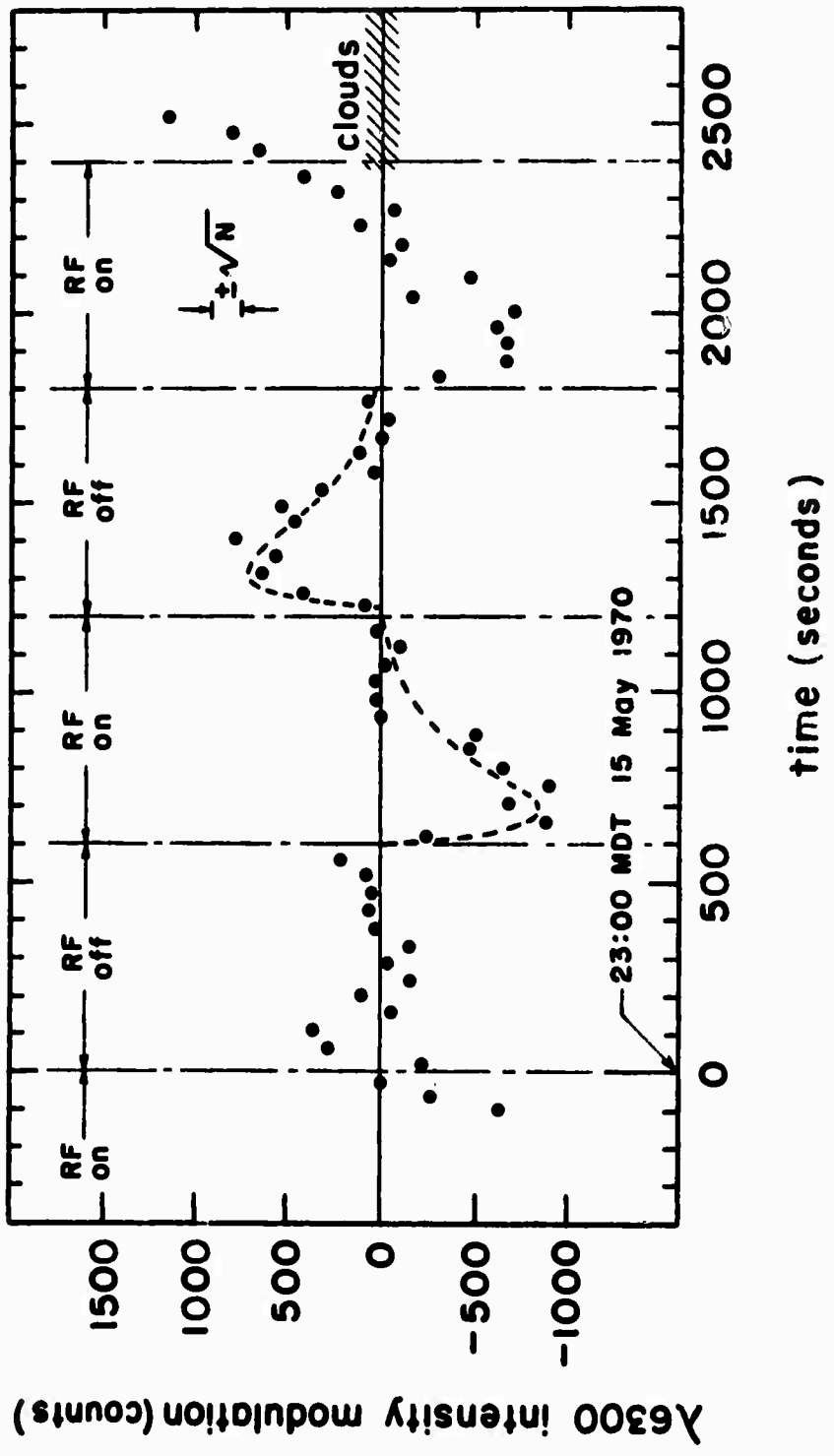
λ6300 intensity modulation (counts)
1500
1000
500
0
-500
-1000
RF on
RF off
RF on
RF off
RF on
±1√N
clouds
23:00 MDT 15 May 1970
0
500
1000
1500
2000
2500
time (seconds)

Figure 1

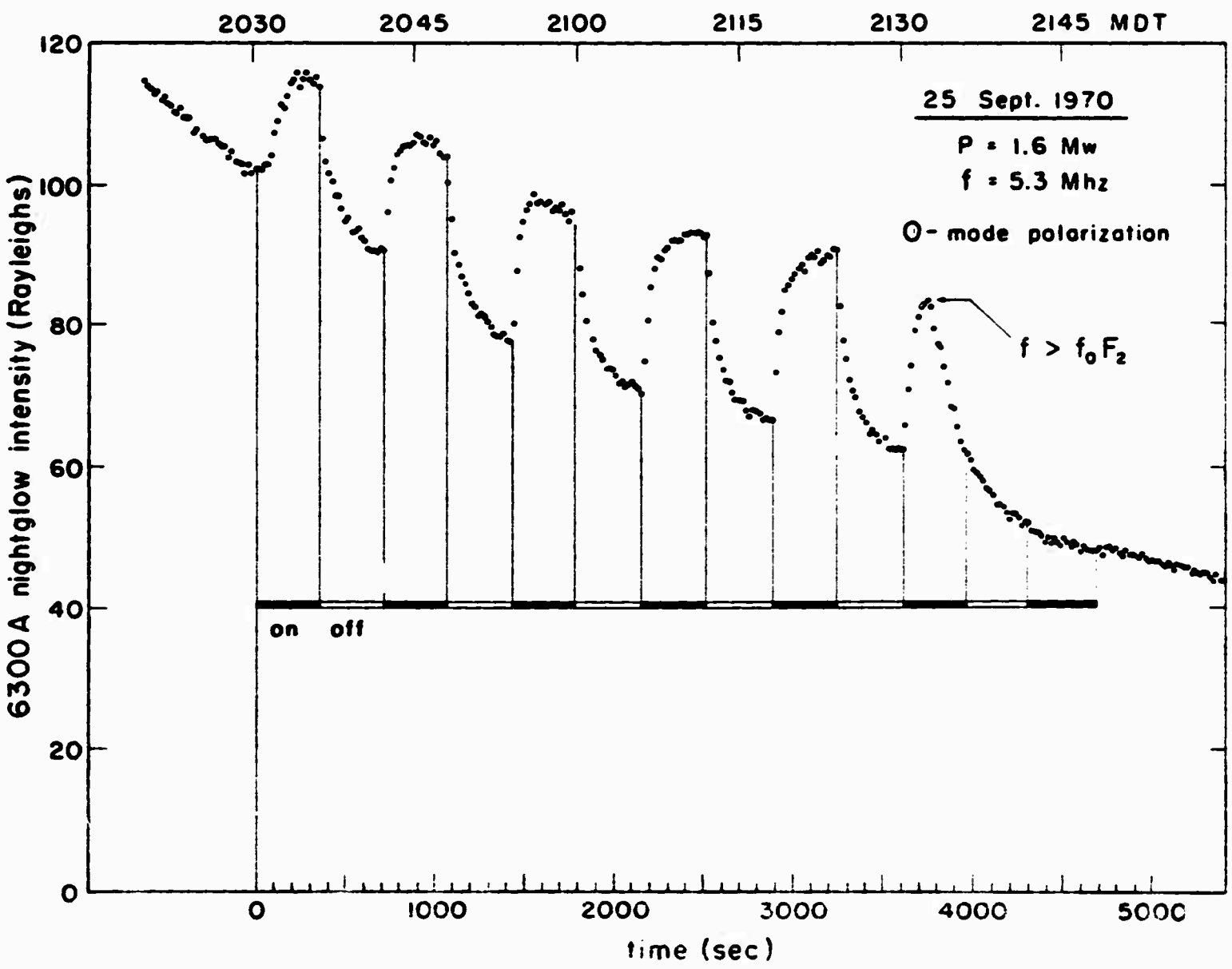
2030
2045
2100
2115
2130
2145 MDT
120
100
80
60
40
20
0
6300 A nightglow intensity (Rayleighs)
25 Sept. 1970
P = 1.6 Mw
f = 5.3 Mhz
O- mode polarization
f > f0F2
on
off
0
1000
2000
3000
4000
5000
time (sec)

Fig. 2

λ 6300 Intensity Modulation – 30 Oct. '70 1810 MST

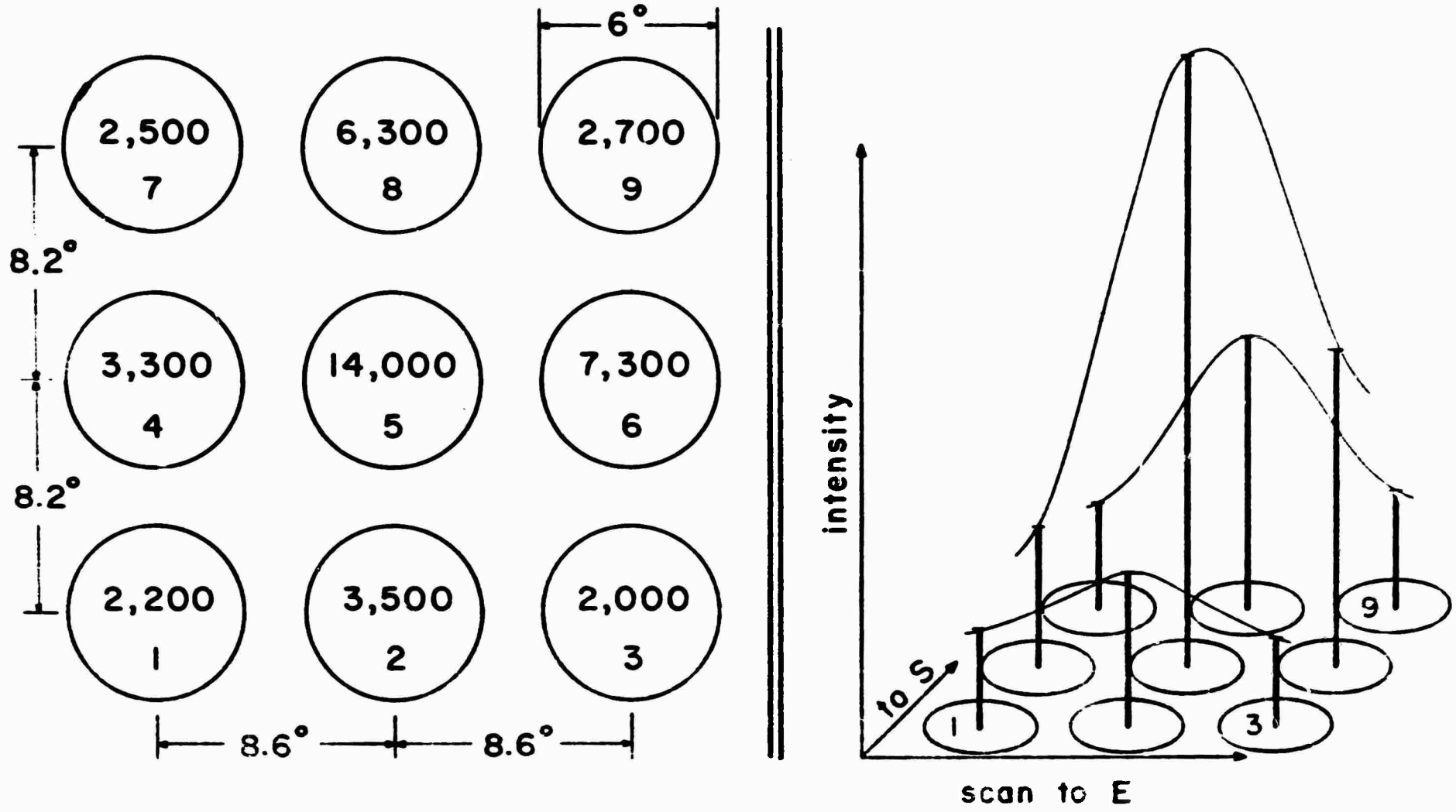

Figure 3

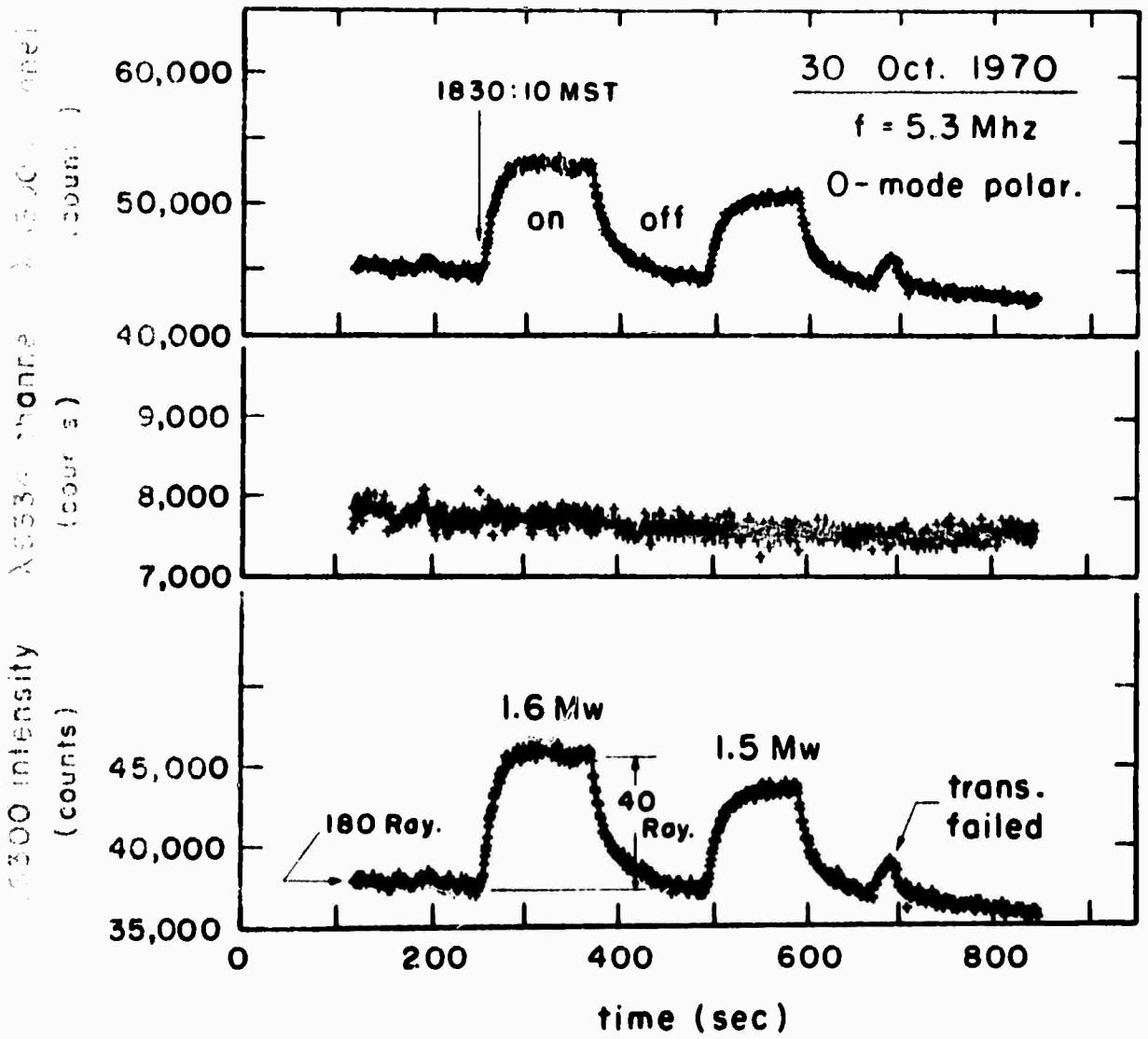
60,000
50,000
40,000
1830:10 MST
30 Oct. 1970
f = 5.3 Mhz
O-mode polar.
on
off
9,000
8,000
7,000
1.6 Mw
1.5 Mw
45,000
40,000
35,000
180 Roy.
40
Roy.
trans.
failed
0
200
400
600
800
time (sec)

Figure 4

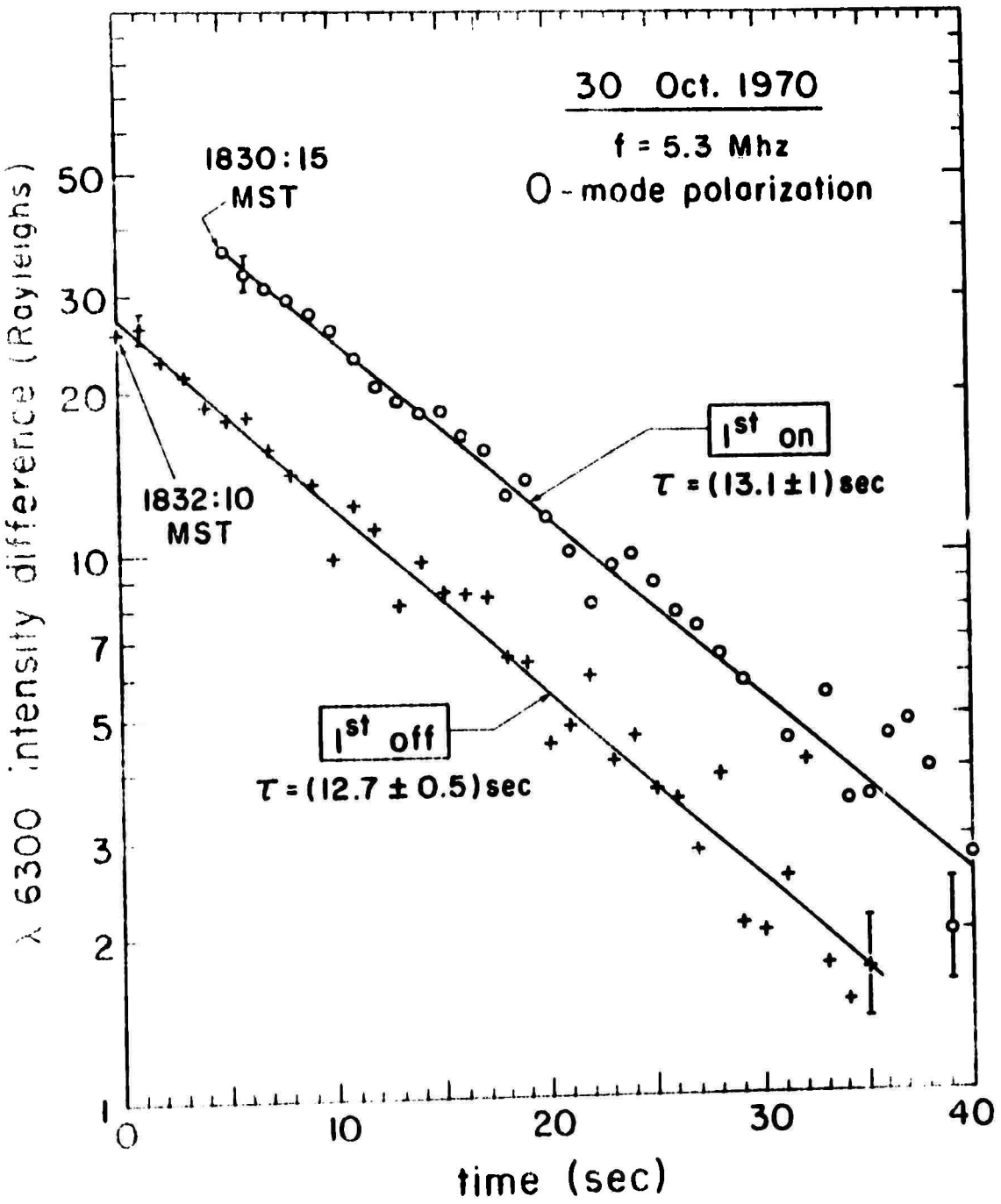
30 Oct. 1970
f = 5.3 Mhz
O - mode polarization
1830:15
MST
1832:10
MST
1st on
τ = (13.1 ± 1) sec
1st off
τ = (12.7 ± 0.5) sec
λ 6300 intensity difference (Rayleighs)
time (sec)
50
30
20
10
7
5
3
2
1
0
10
20
30
40

Figure 5